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United States, or 20 per cent. of the world's production. The lead-region of South-eastern Missouri produces approximately 22 per cent. of the output of the United States, or 7 per cent. of that of the world. If the lead-output of the Joplin region and that of the upper Mississippi mines be added, these figures would be considerably increased. In addition to lead and zinc, the mines of South-eastern Missouri produce an important portion of the American output of barytes, and the mines of Southern Illinois and the adjacent portion of Kentucky yield the bulk of the fluorspar mined in the United States.

## II.—Historical Summary.

Mining in the Mississippi valley dates back to the earliest period of its exploration and settlement by whites. Indeed it was the hope of mineral wealth which attracted the first Spanish and French explorers to the region, and the finding of lead brought about the first attempt at regular settlement. Le Sueur, in 1700 or po[illegible]bly earlier, first noted the presence of lead in the valley. [illegible]st attempt to work the mines was made in Missouri in 1720 [illegible]e "Company of the West," organized in France by John [illegible] out Renault and La Motte, who began mining in the Oza[illegible]he famous La Motte mine was opened at that time, and has b[illegible]orked more or less constantly ever since. The upper mines were not worked until a half-century later. From 1788 to 1810, they were actively operated by Julien Dubuque. In the earlier half of the nineteenth century, the upper mines were by far the more productive and important, but for some years the lower mines have been much the heavier producers.

In the course of the development of the region, it has been studied by the principal American and foreign geologists and mining-engineers, and much that is interesting relating to ore-deposits has been learned. The history of these investigations will be found in reports on Wisconsin,* on Iowa,† and on Missouri.‡ The ore-deposits of the valley are very exceptional in that they are in a region almost entirely free from intrusions of igneous

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* "The Ore-deposits of South-western Wisconsin," by Prof. T. C. Chamberlin. *Geology of Wisconsin*, 1882, vol. iv., pages 365 to 571.

† "Geology of Dubuque County," by Messrs. Samuel Calvin and H. F. Bain, *Iowa Geological Survey, Annual Report for 1899*, 1900, vol. x., pages 379 to 651.

‡ "Lead- and Zinc-deposits," by Mr. Arthur Winslow, *Missouri Geological Survey*, 1894, vols. vi. and vii.

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rocks and in rocks which have not been subjected to severe orogenic forces. It is a great area of generally little disturbed sedimentary rocks, mainly of Palæozoic age.

The present paper is concerned with certain general problems of the region relating particularly to the genesis of the ores and the principles which controlled their deposition. It is believed that these principles have wide application not only to lead- and zinc-ore but to ore-deposits in general, and that a brief general statement of them and the evidence for their application in this region will be of benefit elsewhere. The main outlines of the theory of genesis herein discussed were developed by the senior author of this paper in the course of his studies for the United States Geological Survey. In 1899, after a brief study of the Wisconsin lead- and zinc-mines, the principles were found to apply to the upper mines. A general statement of the whole case was made in a paper read before the Washington meeting of the American Institute of Mining Engineers.* The first application of these principles to lead- and zinc-ores was made in the Iowa-Wisconsin district, and a historical stateme[illegible]ld naturally require that that district be first treated. It i[illegible]y ways advantageous, however, to describe first the district[illegible]Ozarks, since in certain particulars the application of the[illegible] is much more certain there than in the district to which it w[illegible]rst applied. The Missouri-Kansas or South-western Missouri district has been studied in considerable detail by the junior author under the direction of the senior author.† Its greater economic importance makes it better known, and this is another reason for devoting the major part of a necessarily short paper to it.

## III.—Regions and Districts recognized.

The lead- and zinc-mines of the Mississippi valley may be divided into three divisions: (1) those of the Ozark region; (2) those of the Upper Mississippi valley region; and (3) those of outlying districts. Of these, the first, that of the Ozark region, is by far of the greatest importance, and includes four districts, namely, the Missouri-Kansas district, the South-eastern Missouri district, the Central Missouri district, and the North Arkansas district. The Upper Mississippi valley includes a single district, that of Wisconsin, Iowa and Illinois. The outlying districts are two in number: namely, that of Southern Arkansas, and that of Illinois and Kentucky. Therefore there are in the Mississippi valley seven districts which will be treated in order, as follows:—

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* "Some Principles controlling the Deposition of Ores," by Mr. C. R. Van Hise, *Transactions of the American Institute of Mining Engineers*, 1901, vol. xxx., pages 27 to 177.

† "Preliminary Report on the Lead- and Zinc-deposits of the Ozark Region," by Mr. H. F. Bain; with an "Introduction," by Prof. C. R. van Hise; and chapters on the "Physiography and Geology," by Mr. George I. Adams, *Twenty-second Annual Report of the United States Geological Survey*, part ii., pages 23 to 227, 38 figures, and plates VI. to XXV., and pocket-map.

1. The Missouri-Kansas district of which Joplin in Missouri, and Galena in Kansas are the best-known towns. This is essentially a zinc-producing district, though an important amount of lead-ore is also mined. It is characterized by great irregular runs of rich ore.

2. The South-eastern Missouri district, essentially lead-producing and largely known because of its disseminated ores and the large mining and milling operations, which that form of deposit has made possible. The La Motte, Bonne Terre, Doe Run and Flat River mines are typical.

3. The Central Missouri district, an area of indefinite outline not yet fully prospected, and characterized so far as yet developed by small ore-bodies of both lead and zinc.

4. The North Arkansas district, an extensive area, as yet only partially prospected and almost wholly undeveloped, but showing a wide variety of rich zinc-ores and some very promising prospects. Yellville is perhaps the best known town in the district.

5. The Wisconsin-Iowa-Illinois district was an early and important producer of lead; but during its middle and later history, nearly up to the present time, it has principally produced carbonate-of-zinc-ores. Sulphide ore-bodies occur in the district, and are now being marketed to a notable extent. Mineral Point, Platteville and Highland, Wisconsin; Dubuque, Iowa; and Galena, Illinois, are important centres of production.

6. The South Arkansas district, comprising a part of the Ouachita mountains, in which zinc and lead occur in fissure-veins accompanied by small amounts of gold and silver. In character and genesis, the ores of this area seem to vary notably from those of the districts previously enumerated. They have not yet been studied in detail, and are not especially considered in this paper.

7. The Illinois-Kentucky district, characterized by the presence of both lead and zinc, accompanied by notable amounts of

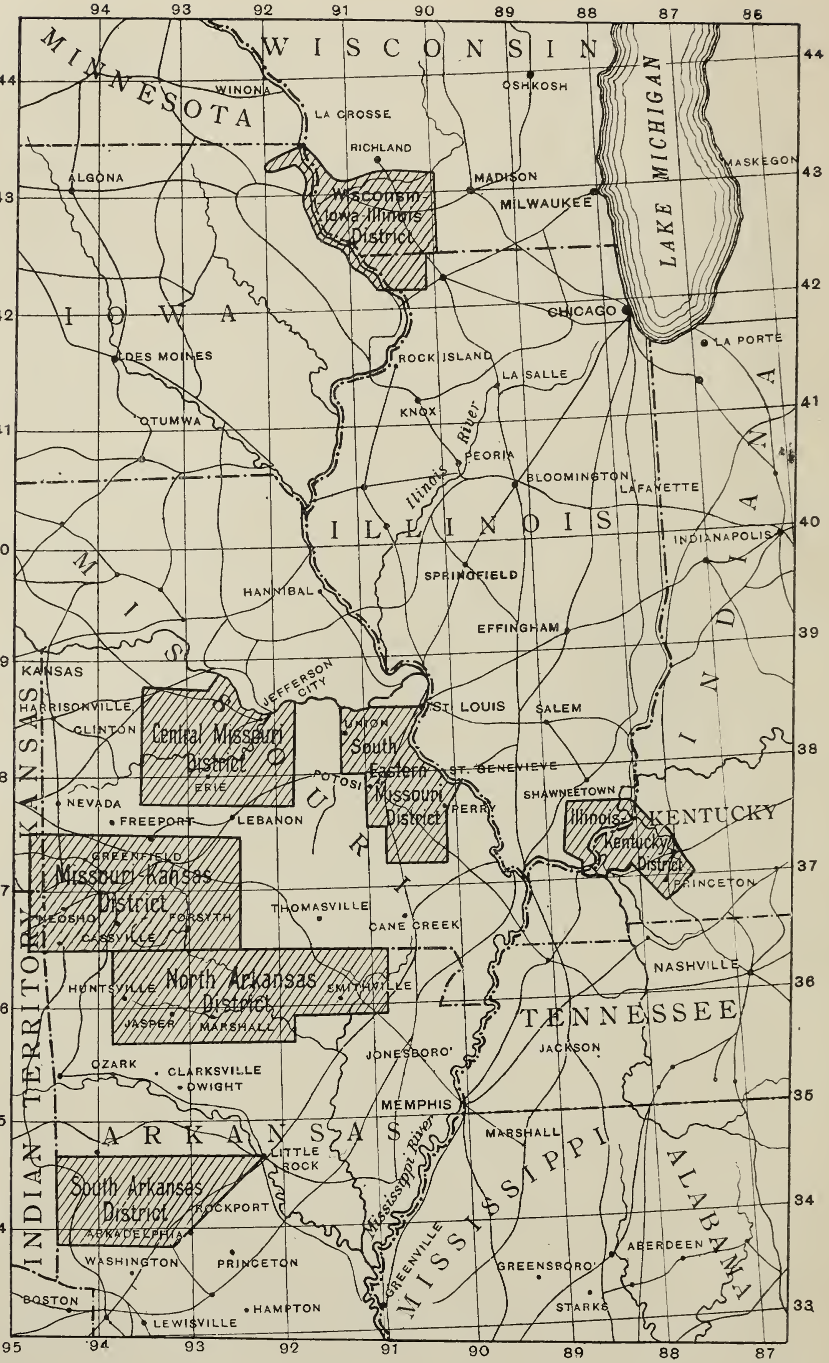

FIG. 1.—MAP OF THE LEAD- AND ZINC-DISTRICTS OF THE MISSISSIPPI VALLEY, FROM OFFICIAL SURVEYS, 1901. SCALE, ABOUT 120 MILES TO 1 INCH.

fluorspar, an association unique so far as the ores of the Mississippi valley are concerned, but linking them in character with the ores of the North of England.

The general geography of the valley and the location of the various districts are shown on the accompanying map (Fig. 1).

## IV.—The Ozark Region.

### A. *General Description.*

The Ozark region is a roughly elliptical area, approximately 300 miles in length from north-east to south-west and 200 miles in breadth. It embraces the southern half of Missouri, the northern third of Arkansas, and small adjacent portions of Illinois, Kansas and Indian Territory. In general structure it is a low, shield-shaped dome bevelled by erosion, with the oldest strata exposed a little north-east of the centre, and the younger beds concentrically disposed about this core of older rocks. This general structure is well shown in Fig. 2, a generalized cross-section from west to east. In Fig. 3, a generalized section from north to south is represented; but the section being taken somewhat west of the structural centre of the uplift, the oldest rocks are not shown. The rocks which are exposed in the region in order of age are as follows:—

1.—*Pre-Cambrian.* The pre-Cambrian is a group of crystalline rocks, mainly granites and porphyries, but with minor masses of basic dykes. These rocks form the core of the St. Francis mountains. Similar rocks have been encountered in other parts of the region in deep drill-holes, and on the western flank of the uplift there are small outcrops of rock presumably belonging to this group. The pre-Cambrian forms the base or floor upon which the sedimentary rocks were laid down.

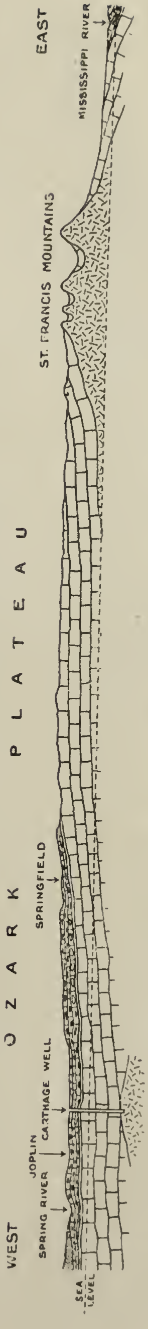

Fig. 2.—Generalized Geological Cross-section of the Ozark Uplift, from West to East, by Mr. George I. Adams.

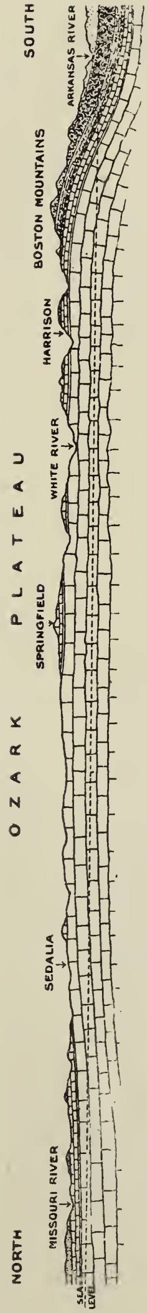

Fig. 3.—Generalized Geological Cross-section of the Ozark Uplift, from North to South, by Mr. George I. Adams.

2.—*Cambro-Silurian.* The lowest series of sediments are Cambro-Silurian magnesian limestones, dolomites and sandstones. The exact sequence has not been worked out, except in certain small areas; and for the present purpose it is necessary to treat the series as a unit. It has a general thickness varying from 1,500 to 2,000 feet.

3.—*Devonian.* Strata belonging to the Devonian system have been recognized only along the north-eastern border of the uplift. A predominantly shaly bed showing affinities to both the Devonian and the Lower Carboniferous is found, however, almost entirely around the uplift. This shale, for convenience called the Eureka-Kinderhook, while thin, is of great significance in its relations to the ore-deposits.

4.—*Lower Carboniferous.* The Lower Carboniferous is represented by an important series of non-magnesian limestones, which contain the ore-bodies, and attains a thickness of approximately 400 feet in the Missouri-Kansas district.

5.—*Upper Carboniferous.* Above the Lower Carboniferous limestones and fringing the uplift (except to the south-east where a recent fault brings the Tertiary into juxtaposition with the Cambro-Silurian) is a thick series of shales and sandstones belonging to the Coal-measures of the Upper Carboniferous.

The Cambro-Silurian rests in marked unconformity upon the pre-Cambrian. The Eureka-Kinderhook shale is in turn unconformable with the Cambro-Silurian, although in this case the plane of unconformability is a remarkably even plane. The Lower Carboniferous limestones are conformable among themselves and with the Eureka-Kinderhook shale. The Upper Carboniferous lies in marked unconformity upon the Lower Carboniferous limestones. The limestone-surface, upon which the shales were laid down, had evidently been subjected to vigorous erosion, and was cut with deep channels and basins at the time when the shales and sandstones began to be deposited over it.

The general lithologic sequence present in the Ozark region from the top downward is as follows:—

1. Thick shale and sandstone.
2. Non-magnesian limestone and chert.
3. Shale, thin.
4. Magnesian limestones, dolomites and sandstones.
5. Crystalline rocks.

It is probable that, at one time, the younger rocks completely covered the older, but as a result of erosion they now crop out in fringing-belts around the central core of older rocks.

The structure of the uplift seems to be due to relatively recent earth-movements, possibly going as far back as the Cretaceous, but occurring probably chiefly in the Tertiary. The exact character of these movements has not been worked out, but the result has been the production of slight quaquaversal dips of 10 to 20 feet to the mile, which seem most pronounced around the edge of the uplift. Widespread but slight faulting and considerable brecciation is present, and seems to have accompanied the uplift.

## B. *Missouri-Kansas District.*

### 1. Stratigraphy.

The Missouri-Kansas district is located on the western flank of the Ozark uplift. It is a large district, although the principal mines are located in certain circumscribed sub-districts with, as usual, relatively broad and barren areas between them. The entire series of rocks, already enumerated, crop out within the district, but the ore-bodies are in the main confined to the Lower Carboniferous limestone. This limestone is coarsely crystalline and non-magnesian; and it carries an abundant fauna related to the Burlington and Keokuk faunas of the Lower Carboniferous series. While the limestone is almost holocrystalline, the perfection of the fossils indicate that it has been metamorphosed through the agency of circulating waters without mashing. In this and all essential particulars of character and composition, the limestone is closely similar to the Lower Carboniferous limestone developed elsewhere in the Mississippi valley, entirely outside of the ore-bearing districts. It is impossible to escape the conviction that the ores associated with these beds are secondary. It is also clear that there was a widespread and presumably long-continued circulation of underground waters in the limestone, not only where ores occur, but throughout the Mississippi valley. Associated with the limestone and interbedded with it are considerable bodies of white chert. Whether this chert be primary or secondary as regards the limestone is not altogether clear. In part, it is a replacement of the limestone, and it is not impossible that in the main it is of this nature. But macroscopic and microscopic studies indicate that the white chert is older than the ores, because in no case has any ore been found entirely surrounded by the chert. The ores and the chert are very closely associated, but in every case observed the association is secondary: the ore occupying cracks and fissures in the chert, or forming a matrix around chert-fragments, where the chert has been crushed.

An important fact in connection with the genesis of the ores is the association of asphalt with the limestone. This is not altogether unknown elsewhere in the Mississippi valley, geodes in the Keokuk limestone at Keokuk, having been found full of this material. However, in the vicinity of Joplin and other producing sub-districts, the quantity of asphalt is rather unusual. At the Kingfisher mine, in Chitwood Hollow, the amount is so great as seriously to interfere with the cleaning of the ore, the crushed material coming from the rolls consisting of white chips of chert or limestone with a dark matrix of asphalt, resembling a mastic prepared for street-paving.

As is well known, limestones are relatively soluble by ordinary underground waters. In the district under discussion, large caves and minor open cavities are not infrequent. In places where the calcium carbonate has been entirely dissolved, it is usual to find a dark insoluble residue which contains important amounts of organic matter. The limestone is evidently rather heavily charged with organic matter. Presumably underground waters passing through the limestone for considerable distances would become a reducing chemical agent.

Above the Lower Carboniferous limestone are scattered patches of dark bituminous shale and, occasionally, bodies of sandstone, which represent erosion-remnants of the Coal-measures that formerly covered the entire district. In part these remnants occupy pre-Coal-measure erosion-basins and have as a result been protected from erosion. In part, they represent blocks faulted down into the underlying beds.

Below the Lower Carboniferous limestone is the Eureka-Kinderhook shale. In the Ozark region, in general, this formation is a shale. In the south-western districts, it is a rather shaly limestone, and as such has heretofore largely escaped notice in such drill-holes as have penetrated it. The formation, normally, 50 to 75 feet thick, is heavily charged with organic matter, and is so firm and close as to constitute, except when broken by fault-planes, an impervious barrier separating the waters circulating in the Lower Carboniferous limestones from those circulating in the Cambro-Silurian.

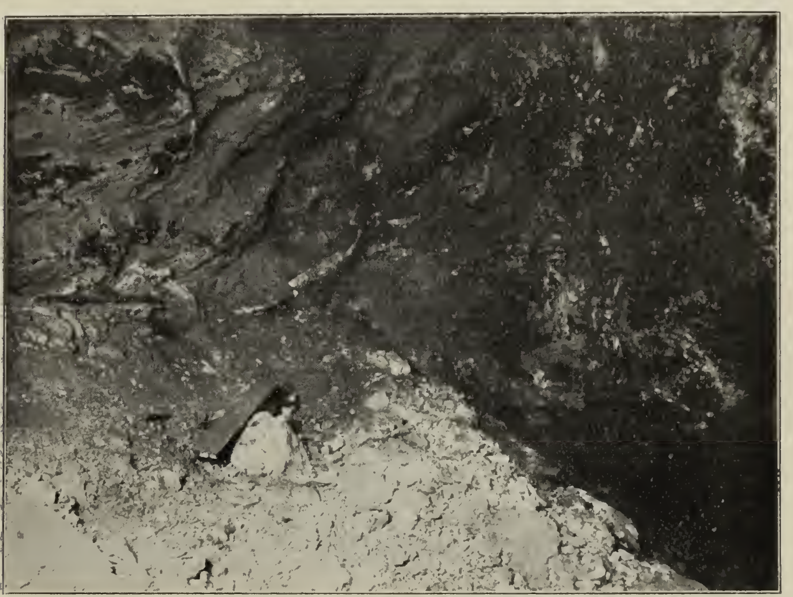

Fig. 4.—Fault in the Slaight Mine, Webb City, Missouri.

The Cambro-Silurian rocks are principally known in the district through drill-holes or records. They form a great series of rocks of very uniform character, underlying at considerable depths the entire district. Since the dip of the rocks from the centre of the Ozark uplift is greater than the slope of the surface, their area of outcrop to the east is considerably higher than the surface of the ore-bearing district. Indeed the open plain, upon which

Joplin, Galena, Webb City, Cartersville, Aurora and other mining camps are situated, lies some 600 to 700 feet below the outcrop of the Cambro-Silurian beds; although in these camps the Cambro-Silurian is at considerable depths. As a result, surface-waters falling on the area of outcrop and sinking into the Cambro-Silurian strata find their way down along the dip, under the impervious Eureka-Kinderhook shale. In the mining district, this water is under a considerable hydrostatic head and it rises to the surface whenever there is an opportunity. As a result, artesian wells are not unknown, and in the deeper mines there is a steady upward flow of water, which bears no relation whatever to local rainfall or seasonal changes.

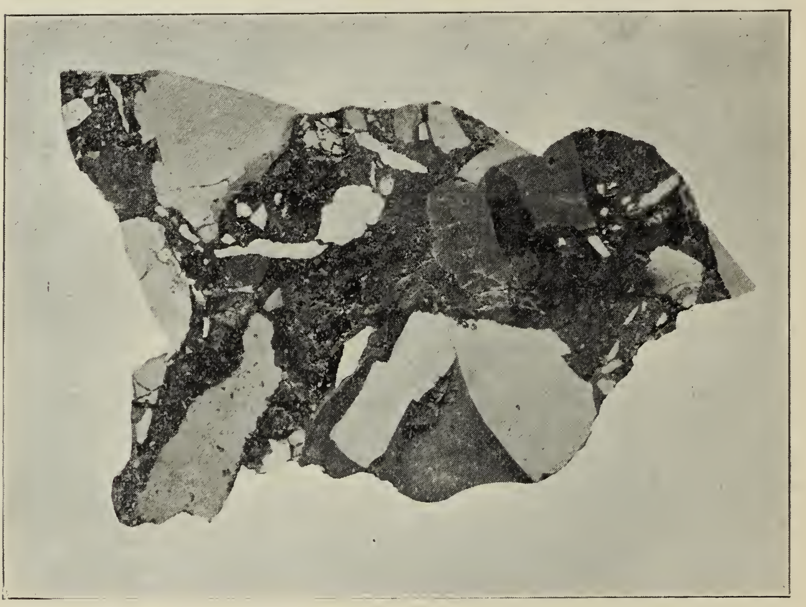

FIG. 5.—CHARACTERISTIC BRECCIA OF THE SOUTH-WESTERN DISTRICT, FROM JOPLIN, MISSOURI.

The opportunity for the water of this deep circulation to ascend to the Carboniferous Limestones and through them to the surface, is afforded by numerous faults which break through the intervening shales. These faults, where observed, are rarely single sharp fault-planes, but are a series of fracture-planes or zones of fracture. They are usually accompanied, in the Carboniferous Limestone, by brecciation and clear evidence of extensive solution and deposition by underground waters. Such faults have been directly observed among other places in the Slaight (Fig. 4), and other mines of the Missouri Zinc-fields at Cartersville, Missouri, in the Circle mines at Oronogo, in the Boston-Aurora, the Sand Ridge and other mines at Aurora, and in numerous mines on the Continental Tract at Joplin. One of these faults has been studied and traced in the Fields down into the Cambro-Silurian on Pierson Creek in Missouri, by Prof. Shepard,* and many others are known to occur.

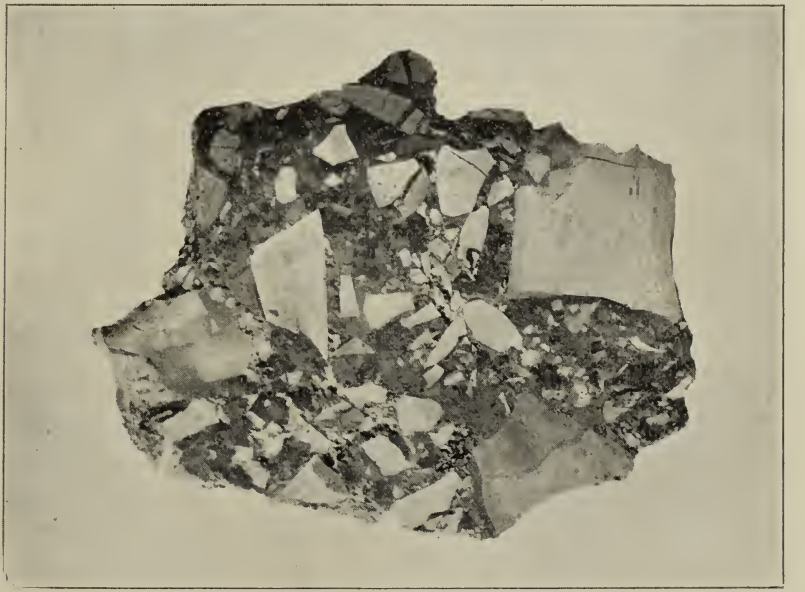

FIG. 6.—CHARACTERISTIC BRECCIA OF THE SOUTH-WESTERN DISTRICT, FROM PEORIA, INDIAN TERRITORY.

The manner by which the character of the displacement is affected by the nature of the country-rock in this district is both interesting and instructive. The Cambro-Silurian rocks are thickly bedded, homogeneous dolomites. Stresses generated in them or transferred to them accumulate, and are eventually relieved by extensive, clean-cut fractures. The Eureka-Kinderhook, being a shale, yields normally by flexure rather than by fracture, and the same is true of the overlying shales of the Coal-measures. Where the shale is thin or, as is true of the Eureka-

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* "Geology of Greene County," by Prof. E. M. Shepard, *Missouri Geological Survey*, 1888, vol. xii., part 1, pages 174 *et seq.;* and for additional details, see "Lead and Zinc-deposits of the Ozark region," *Twenty-second Annual Report of the United States Geological Survey*, part ii., pages 168 to 173.

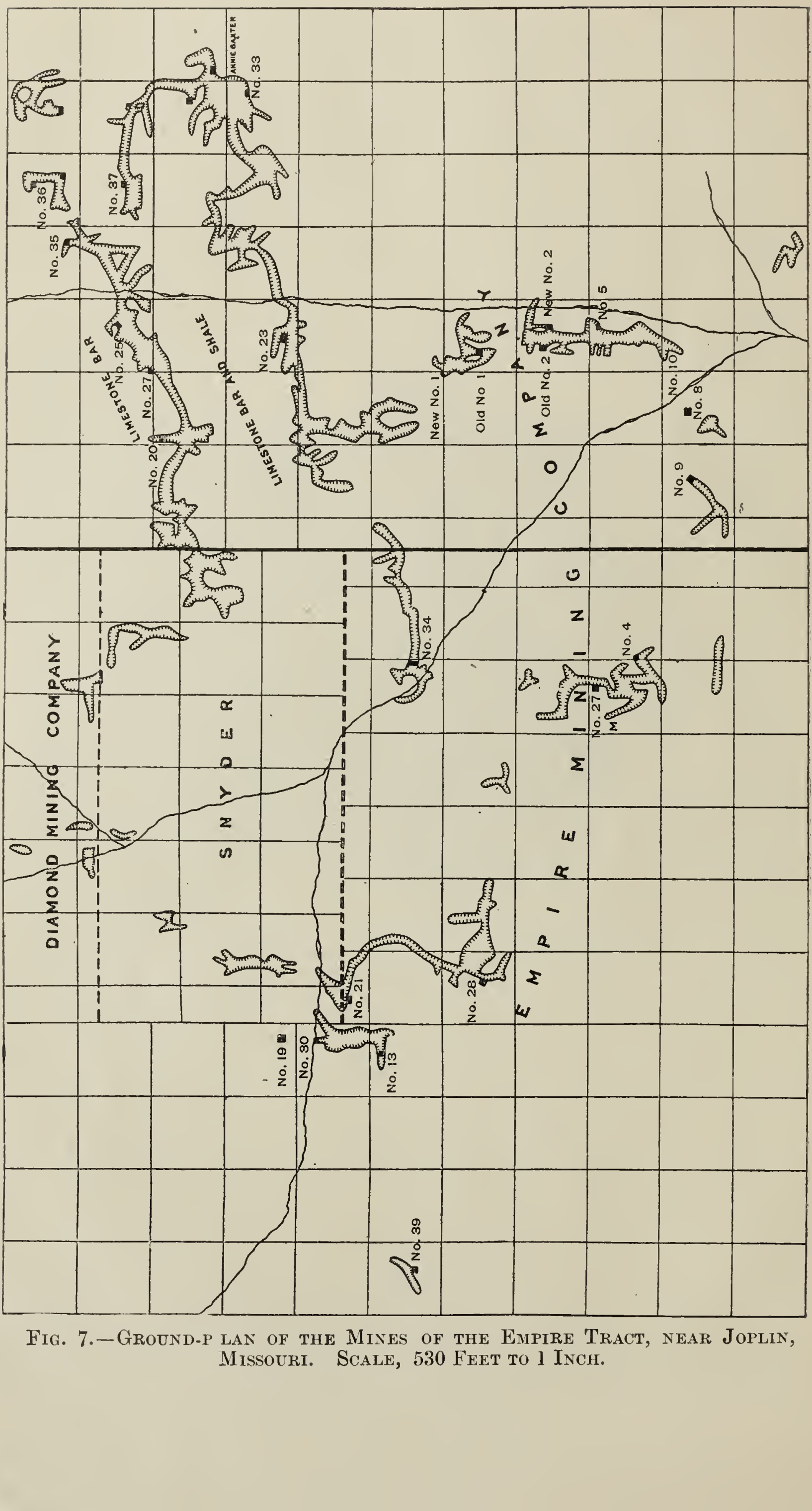

Fig. 7.—Ground-plan of the Mines of the Empire Tract, near Joplin, Missouri. Scale, 530 Feet to 1 Inch.

Kinderhook in this district, so calcareous as to be a brittle, shaly limestone, the stresses have also produced fractures. The Lower Carboniferous Limestone is more thinly bedded than the Cambro-Silurian limestone and is much less homogeneous. As a result, deformation is normally accomplished in them by means of many minor fractures. The chert, which accompanies the limestone, is exceedingly brittle and is fractured and brecciated by relatively weak stresses. The limestone being soluble is easily and quickly removed from a brecciated mass of limestone and chert, leaving the small, sharp-angled bits of chert to be re-cemented by material brought in by the solutions. Breccias of this kind are illustrated in Figs. 5 and 6.

The exceedingly irregular outline of the ore-bodies, illustrated in the ground-plan (Fig. 7), is the result of deformation followed by solution and deposition in interbedded brittle chert and soft soluble limestone. It will be noted that while in detail the ore-bodies, as shown by the workings, are exceedingly irregular, in general they are arranged along certain rude lines, which represent the zones of fracture in the limestone and chert. The relations of the ore-bodies to fault-blocks is also shown in the ground-plan of the Oronogo Circle mines (Fig. 8). The same stresses, which in the Carboniferous Limestone produced an irregular breccia, in the more homogeneous Cambro-Silurian limestones probably produced a simple regular fracture-plane, such as commonly gives form to the ore-bodies occurring in the Cambro-Silurian elsewhere in the Ozark region. The stresses acting on the Eureka-Kinderhook shale would probably have been relieved entirely by flexure, if it were not for the calcareous, brittle nature of these beds within the mining district.

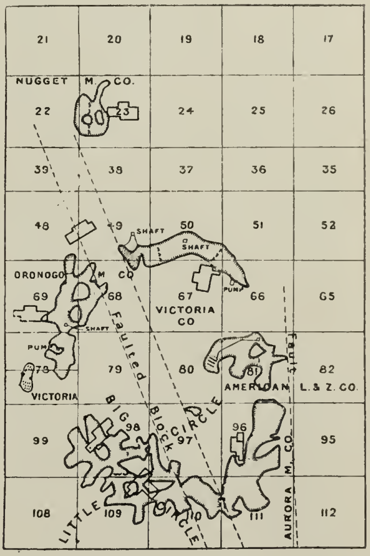

FIG. 8.—GROUND-PLAN OF THE MINES OF THE ORONOGO CIRCLE, ORONOGO, MISSOURI. SCALE, 530 FEET TO 1 INCH.

Certain of the fracture-planes are marked by faulting and the measured throw, 100 to 175 feet, makes it clear that these faults extend down into the Cambro - Silurian. The fault-planes thus afford opportunities for artesian waters, within the Cambro-Silurian, to rise into the irregular brecciated belts of the Lower Carboniferous.

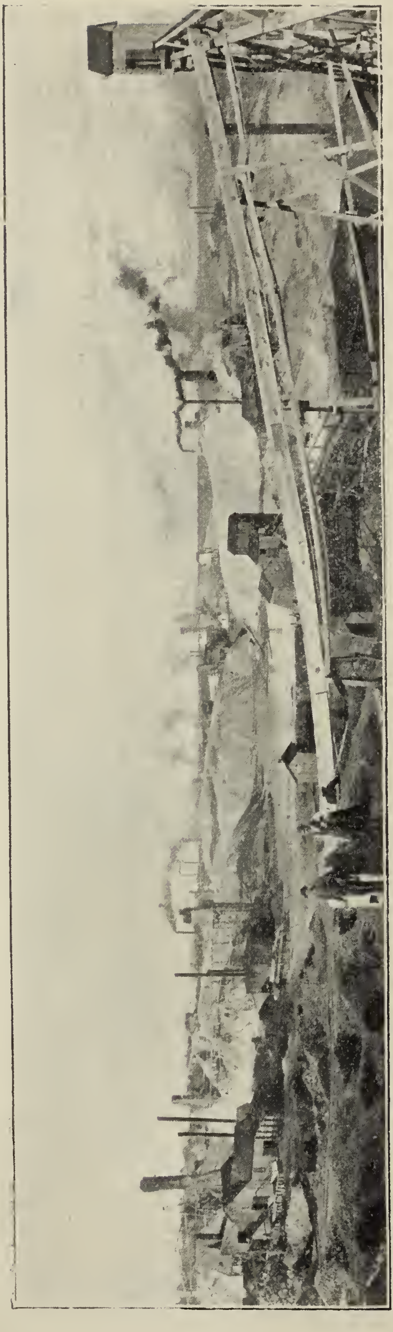

Fig. 9.—Zinc-mines near Webb City, Missouri, illustrating the Usual Style of Plant and the Large Number of Mines in a Given Area.

### 2. Ores and Ore-bodies.

The ores of the district are those of lead and zinc, and both occur predominantly in the sulphide form. Minor amounts of carbonate of lead and considerable amounts of hydrous silicate of zinc are mined. In former years, the relative amounts of the oxidised compounds were much greater. The lead- and zinc-minerals are accompanied by iron and copper sulphides with their carbonate and oxide derivatives; but the quantities of the copper minerals are very small. Dolomite is constantly found in large quantities, and both baryte and quartz (crystallized) locally occur in notable quantity. A black, recently deposited chert is an exceedingly common gangue-mineral. Cadmium sulphide is not infrequent. The ore-bodies are large in size, but discontinuous and very irregular. This has had an important influence upon mining operations, there having been many small mines of short life. The general character of the mine-plants is shown in Figs 9 and 10.

There are three common classes of ore-bodies :—

(*a*) The first class of ore-bodies comprize those in which the lead and zinc occur exclusively as sulphides, and usually thoroughly mingled. They are accompanied by marcasite, pyrite and chalcopyrite. Pink crystallized dolomite and occasionally small crystals of quartz occur in abundance. Adjacent to the ore-bodies, a grey massive dolomite has developed from the limestone. The ore-bodies are traversed by open water-channels and show many vughs, varying in size from small openings to those several feet across. These channels and vughs are lined with beautiful crystals of the various minerals enumerated, and with these calcite is abundant. The water found in connection with the ore-bodies of the first-class is clear as crystal, and the flow bears no relations to

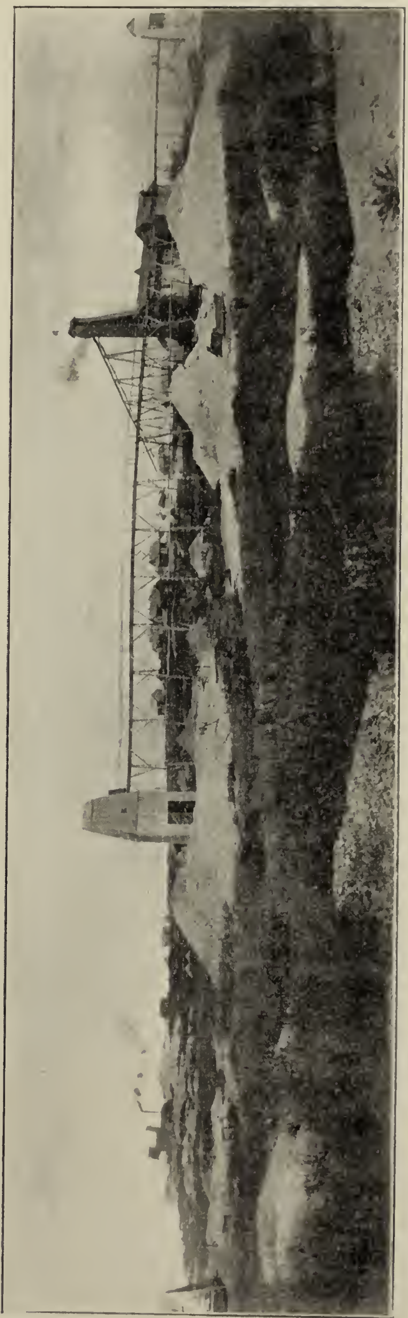

Fig. 10.—Zinc-mines near Joplin, Missouri, illustrating two Shafts delivering Ore by an Elevated Track to a Concentrating-mill.

local rainfall or seasonal changes. All such ore-bodies are below the normal underground water-level, and at greater depth than the second and third classes described below. As will be later explained, these ore-bodies represent the first or original concentration of the ore.

(*b*) Above the ore-bodies just described, at and extending for some distance below water-level, are ore-bodies of a second class. These are largely composed of sphalerite. In all cases this mineral is notably dominant. They are normally considerably richer than the ore-bodies just described. The ground is softer and requires more timbering. The water may be dirty, and in some instances varies in quantity. In certain cases, in vughs and cracks in the ore, there is a secondary deposition of the sulphides, the latter occurring either in well-defined crystals or as a cement joining fractured portions of the original ore. In certain cases, notably in the mines of the Boston-get-there Company, mingled with these secondary or recent sulphides are crystals of siderite. These ore-bodies are those now most frequently worked, and, as fully explained later, are believed to represent original ore-bodies enriched by secondary deposition of sulphides.

(*c*) The third class of ores are those above water-level, or in some instances in part slightly below that level. These ores consist essentially of either galena or calamine. The ground is either dry or muddy. Red clay is the most constant gangue. The beautiful crystals found in the ore-bodies first described are relatively rare. The amount of water handled by the mine-pumps is closely dependent upon seasonal variations and local rainfall. Such carbonate of zinc and lead as occurs is found in connection with these ore-bodies. Baryte is also found with them. Stains of copper carbonate are not infrequent. As explained later, these ore-bodies are believed to represent the accumulations due to oxide-enrichment. They are broadly equivalent to the usual gossan of metalliferous veins.

The forms of the ore-bodies are conditioned by the form of the openings produced by fracture and solution, as already explained, and the extent to which the metal-bearing solutions penetrating the surrounding limestone have metasomatically replaced the latter. As already indicated, the normal form of ore-body is exceedingly irregular. This does not, however, preclude the occurrence of exceptional, relatively regular, ore-bodies. The ore-deposits of the Boston-get-there mine (Fig. 11) represent one of the common regular forms known locally as "sheet-ground." In this instance, the ore-bearing solutions have spread out along bedding-planes in the top of a great body of chert. The result has been the formation of a great blanket-deposit, 10 to 20 feet thick. The whole is mined, except where it is necessary to leave pillars to support the limestone-roof.

The vertical distribution of the ores is that common in the lead- and zinc-districts of the entire Mississippi valley. The carbonates, silicates and oxides, where they occur, are found above or near water-level, and constitute the highest portion of the ore-bodies. Below them the sulphides are found. To a limited extent, the sulphides are mingled with the carbonates and silicates, the line of demarcation not being everywhere sharp. It is noteworthy that of the sulphides thus mingled, galena is the most frequent. The sulphides commonly exhibit a vertical order among themselves, there being three zones in which galena, blende and iron sulphides become in turn dominant with increased depth. The zone of dominant iron sulphides has not as yet been generally penetrated in this district. Indeed, throughout the district iron sulphides are very much less abundant than is common in other districts. Below the three zones mentioned, where the three sulphides are thoroughly mingled, in this district zinc sulphide seems usually dominant.

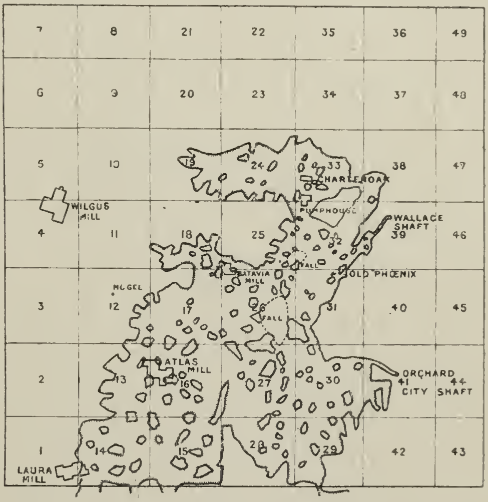

FIG. 11.—PLAN OF THE BOSTON-GET-THERE ZINC-MINES, PROSPERITY, MISSOURI. SCALE, 530 FEET TO 1 INCH.

## 3. Genesis of the Ores.

In making a statement as to the genesis of the ores, it will be necessary to state the theory somewhat briefly and to refer to other papers* for many of the details which support it.

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* "Some Principles controlling the Deposition of Ores," by Prof. C. R. Van Hise, *Transactions of the American Institute of Mining Engineers*, 1901, vol. xxx., pages 27 to 177. "The Lead and Zinc-deposits of the Ozark Region," by Mr. H. F. Bain, *Twenty-second Annual Report of the United States Geological Survey*, part ii., pages 203 to 215.

It will be convenient to consider separately the three classes of ore-bodies already described.

### (*a*) Ores of the First Concentration.

A brief field-study makes it clear that the ores of the first class as well as the derived ores of the second and third classes, were deposited from solutions. The reasons for this are so obvious to any student of ore-deposits, who has followed the descriptions given, that it is merely necessary to mention the matter. In every case the ore-bodies are found where there is the clearest evidence of the movement and mingling of considerable bodies of solutions. In sedimentary, undisturbed rocks, such as those of the Mississippi valley, all theories of ore-deposition by sublimation, pneumatolytic action and magmatic differentiation may be at once rejected. The whole of the evidence points to the ores being deposited from the dilute solutions which constitute the ground-water of the district. The precipitation of ores was mainly accomplished by the mingling of solutions at places where ground-waters of different constitutions met. This is perhaps clearest in the case of the ores of the first class. It has already been explained that while the ore-bodies occur mainly in the Carboniferous Limestone, no ore-bodies have been found except in areas where there was opportunity for a mingling of the ground-waters of the Carboniferous and the Cambro-Silurian limestones. The Carboniferous Limestone has been almost completely re-crystallized, and in part at least the older or white chert which is interbanded with the limestone has been developed in it by replacement. These changes occurred anterior to the development of the ore-bodies, and were apparently wholly independent of the processes which developed the ores. There was early, a far-reaching and long-continued circulation in the Carboniferous rocks, which brought about many changes in the limestones and cherts of that formation. So long, however, as there was no connection with the deeper circulation of the Cambro-Silurian, neither dolomite nor ores were developed. This is shown by the fact that in the Mississippian limestones outside the Missouri-Kansas district, in areas where connection with a possible circulation below has never been established, there is a similar re-crystallization of the limestone with the development of chert-nodules and concretions but no ore or dolomite. So long as the circulation was confined to Carboniferous rocks there was no deposition of ore. Only when opportunity was afforded, by deep fault-planes cutting the intervening shale, for the waters of the Cambro-Silurian to rise and mingle with the waters above, was there any considerable ore-deposition ; and it is an interesting confirmation of the correctness of this view that dolomite is a constant accompaniment of the ore. Wells penetrating the Carboniferous rocks, away from the ore-bodies yield water practically free from magnesia. Those penetrating the Cambro-Silurian show that the water is notably charged with magnesia.* This indicates that both the magnesia and the metals now found in the ore-bodies were brought into the Carboniferous rocks from or through the Cambro-Silurian below.

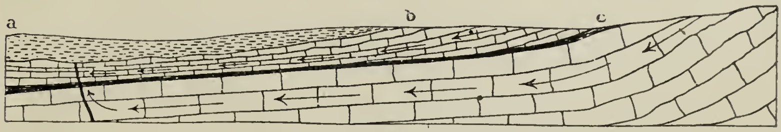

FIG. 12.—IDEAL SECTION INDICATING THE COURSE OF UNDERGROUND WATERS IN THE MISSOURI-KANSAS DISTRICT.

At an earlier period, before the overlying Coal-measure shales were cut through, the general underground circulation was as indicated in Fig. 12. A portion of the water falling on the surface, between *c* and *d*, sank into the ground and took the course indicated by the arrows. As it travelled down the dip, there was an accumulating hydrostatic pressure which tended to force up the water. The overlying impervious Eureka-Kinderhook shale prevented an actual upward flow, until the faulted area near Joplin was reached, where the water passed upward along the fault-planes as indicated. The water falling on the surface, between *b* and *c*, likewise passed down the dip and was prevented from flowing out on the surface by the overlying shale. The water accordingly met and mingled with that rising along the fault-planes. At the point of deposition, there were accordingly two classes of waters, one being ascending and the other moving laterally. If the whole course of either current be taken into account, each will be recognised to have been descending. From any point of view, the major movement is lateral. It is noteworthy that each stream of water derived its motion from gravitative stress. It is also noteworthy that the waters now are, and so far as there is any evidence, always have been at ordinary temperatures. In the journey outlined, neither stream of water reaches depths sufficient to result in any notable increase of temperature. Neither is there any known intrusion of igneous rock in the region which, if present, might have influenced the temperature of the underground water. The circulation outlined represents, in the main, the circulation now obtaining. The differences will be noted later.

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* See analysis in "The Geology of Benton County," by Messrs. F. W. Simonds and T. C. Hopkins, *Annual Report of the Arkansas Geological Survey for 1891*, 1894, vol. ii., pages 19 *et seq.*

It will be here assumed that the metals were derived from the Cambro-Silurian limestone. Evidence on this point is given in the general discussion at the end of this paper. It will there be seen that the metallic sulphides were originally precipitated from the Cambro-Silurian seas. Thus, they were deposited in the Cambro-Silurian limestone in widely dispersed, minute particles.

The chemical processes involved in the segregation and deposition of the ores are believed to be as follows: —

Rain-water falling upon the area of the Cambro-Silurian outcrop is charged with oxygen, and as it passes into and through the rocks this oxygen reacts upon the sulphides of lead, zinc and iron, producing sulphates.

Once oxidized, these metals are taken into solution; for zinc sulphate is very soluble, and lead sulphate, while considered insoluble in the laboratory because at 15° Cent. only about 1 part in 31,000 is dissolved in pure water, is amply soluble so far as the transfer and concentration of lead by underground waters are concerned. It is probably very uncommon for the ore-bearing solutions of the first concentration to carry so much of the metal as 1 part in 100,000.

Rain-water falling upon the area of outcrop of the Carboniferous Limestone expends its oxygen in oxidizing some of the large quantity of asphalt and other organic matter which it meets in its course. But the oxygen is exhausted in the early part of the journey. Organic compounds are then taken into solution. Also one of the most common, if not the invariable accompaniment of waters which have traversed carbonaceous beds, is hydrogen sulphide: this compound being produced by the interaction of the organic compounds and original sulphides, of which the most common is iron sulphide. The water-currents of the Carboniferous Limestone are therefore reducing in character, due both to the organic matter carried and to the hydrogen sulphide contained.

The sulphates formed in the Cambro-Silurian, taken into solution by the underground water, are carried westward, and finally upward to the point of deposition. The long portion of the journey is in the Cambro-Silurian. Opportunity is afforded for the water to deposit its metallic load so soon as reducing agents find it. This is when the water leaves that formation, as is shown by the ores at Granby and elsewhere in the Kinderhook. At the very first contact with the organic matter, widely distributed through these shales and the overlying Carboniferous Limestone, deposition began. We conclude therefore that the Cambro-Silurian limestone was the main original reservoir from which the underground solutions derived their metallic contents.

When the waters of the Carboniferous Limestone meet and mingle with the ascending waters of the Cambro-Silurian limestone, the lead and zinc sulphates are precipitated as sulphides. This is largely due to the direct abstraction of the oxygen of the sulphates by carbonaceous material, it being thus oxidized and the lead and zinc being reduced to and thrown down as sulphides. Also the lead and zinc may be partly precipitated as the result of the action of the hydrogen sulphide. The reactions in this case may be expressed as follows:—$PbSO_4 + H_2S = PbS + H_2SO_4$; and $ZnSO_4 + H_2S = ZnS + H_2SO_4$. The sulphuric acid would react in the presence of limestone and water as follows:—$H_2SO_4 + CaCO_3 + H_2O = CaSO_4 2H_2O + CO_2$. The gypsum being soluble is ordinarily carried away at once in solution. In a few instances some remains behind.

It is not necessary to believe that the ores were entirely precipitated from sulphates. Such a derivation is, however, the simplest hypothesis, and the one which best accords with the facts of the field. In small part, the ores may have been transported as chlorides or carbonates, and in fact there are a large number of possible chemical combinations available.

The ores of the first concentration were deposited in the presence of an excess of precipitating agents. There was more than a sufficient amount of organic material and of hydrogen sulphide to throw down all the metallic compounds; and hence all the sulphides precipitated were intimately mingled. The sulphides thus precipitated were not deposited to an unusual degree contiguous to the black shales of the Eureka-Kinderhook and of the Coal-measures. The probable reason for this is that the precipitation was mainly caused by the solutions, and not by the solid organic matter of the shales. The broken and porous limestone gave much larger openings for the mingling of the solutions and the precipitation of the ores than the plastic shales.

The time of the deposition of the ores of the first concentration is not well fixed. It began after the deformation which fractured and faulted the limestones, and which cut the Eureka-Kinderhook. It seems reasonable to correlate this event with the uplift of the Ozark dome. This movement has been placed by Mr. C. R. Keyes* at the beginning of the Tertiary. This is, however, admittedly uncertain. The deposition continued from that time onward, and since the general movement of the underground water in the district is to-day substantially the same as indicated, it is probable that ores of the first concentration are still being deposited.

### (*b*) Enriched Sulphide-ores.

An important counter-movement of the waters has, however, been in play since the extensive removal by erosion of the cap of Coal-measure shales and limestones. It has been the work of this counter-movement to produce a reconcentration, and the enrichment of the upper sulphide bodies. Other results of this movement have been the production of an orderly vertical arrangement of the ores, and the accumulation of the carbonates, silicates and oxides in the superficial zone.

When, in consequence of erosion, the sulphides of the first concentration rise above the level of the ground-water, they are in the belt of oxidation and are slowly oxidized to sulphates and carbonates. During the formation of sulphates and carbonates, a portion of these salts is dissolved, carried below the level of underground water and reprecipitated as sulphides. They thus contribute to the value of the ores found at and for some distance below this level, and produce a notable enrichment of the ores of this zone. In part, the process is identical with that already discussed in connection with the first concentration of the ore; the difference being that in this case the sulphates are carried downward from above rather than upward from below. In both cases, the organic matter and the hydrogen sulphide present in the solutions of the Carboniferous Limestone are reducing agents. As in the case of the first concentration, sulphates are reduced to sulphides by the organic matter, and the various salts of lead and zinc are precipitated by hydrogen sulphide. Both of these reactions result in sulphide-precipitation and enrichment.

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* "Characteristics of the Ozark Mountains," by Mr. C. R. Keyes, *Missouri Geological Survey*, 1895, vol. viii., pages 351 to 352.

But there is another important series of reactions due to the reducing action of the sulphides themselves, the chief being that between lead and zinc salts and iron sulphide. First, considering the case of lead, and supposing the iron to be in the form of sulphide of iron, the reactions may be written as follows:—$PbSO_4 + FeS = PbS + FeSO_4$; and $PbCO_3 + FeS = PbS + FeCO_3$.

If the iron be in the form of $FeS_2$, as is most likely, oxygen would be necessary for the reactions. The equations would then be as follows:—$PbSO_4 + FeS_2 + O_2 = PbS + FeSO_4 + SO_2$; and $PbCO_3 + FeS_2 + O_2 = PbS + FeCO_3 + SO_2$.

Since zinc sulphide is also present and reacts in a corresponding manner on lead salts, the following reactions may also be supposed to take place:—$PbSO_4 + ZnS = PbS + ZnSO_4$; and $PbCO_3 + FeS_2 + O_2 = PbS + FeCO_3 + SO_2$.

In the case of the latter reaction, smithsonite would be formed; and it is noteworthy that not only in this district, but throughout the Mississippi valley there is a common association of smithsonite and galena.

The relations between iron sulphide and the zinc compounds correspond to those between zinc sulphide and the lead compounds. According to the extent to which the zinc carbonate and sulphate produced by the reactions noted above, or the corresponding compounds produced in the zone of oxidation, are carried down by the waters, there would be a series of reactions as follows:—$ZnCO_3 + FeS = ZnS + FeCO_3$; and $ZnSO_4 + FeS = ZnS + FeSO_4$.

Since of the three metals, lead, zinc and iron, the first has the greatest affinity for sulphur, the second the next greatest, and the last the least, in the presence of downward moving oxygenated waters, the final result of all the reactions is the orderly vertical arrangement of the sulphides already noted as characteristic of this district; that is, galena, blende and iron pyrites successively dominant in depth. Owing to the small amount of iron sulphide present in the district it is unusual here, although common in other mining districts, for the iron actually to dominate the other minerals in depth. Such dominance has, however, been noted in deep drilling at Granby, Missouri, and an increase in the amount of iron sulphide present is noticeable at many points.

The general process of secondary enrichment of sulphide ore-bodies, and the reactions of the sulphides toward each other, has recently been discussed in some detail by Messrs. Van Hise, Emmons, Weed, and others.* It is not intended here to discuss the process farther than its application to the ore-bodies of the region discussed. The widespread orderly vertical arrangement of lead and zinc sulphide bodies indicates, however, that the process has been an important one in the genesis of these ores.

### (*c*) The Oxidized Ores.

The ores of the third class, the oxidized ores, include essentially those above or near the underground water-level. They comprise oxides, carbonates, silicates, sulphates, and occasionally chlorides and other rare combinations. These ore-bodies have been formed from the sulphide-bodies after the overlying impervious shale had been cut away, so as to allow a local downward flow of surface-waters containing oxygen. They are the result of direct oxidation of sulphide ore-bodies of classes (*a*) and (*b*). Their richness is partly due to residual concentration, that is, is due to enrichment which results from the removal by the ordinary process of erosion of the more destructible gangue and country-rock. The formation of the oxidized ores has taken place mainly above the level of the underground-water; since below that level there is usually an excess of organic matter, and hence the medium is reducing. The changes due to oxidation, carbonation, hydration and solution, are coincident with the elevation of the sulphides above the level of the ground-water, in consequence of progressive denudation. Lead sulphide (PbS) and zinc sulphide (ZnS), by simple oxidation are changed to lead sulphate ($PbSO_4$) and zinc sulphate ($ZnSO_4$). The lead sulphate constitutes the mineral anglesite. If this sulphate reacts upon calcium carbonate, lead carbonate and hydrated calcium sulphate are produced according to the following equation:—$PbSO_4$ +

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* "Some Principles controlling the Deposition of Ores," by Prof. C. R. Van Hise, *Transactions of the American Institute of Mining Engineers*, 1901, vol. xxx., pages 27 to 177. "The Secondary Enrichment of Ore-deposits," by Mr. S. F. Emmons, *Ibid.*, pages 177 to 217. "Enrichment of Gold- and- Silver-veins," by Mr. W. H. Weed, *Ibid.*, pages 424 to 448. Also, "Enrichment of Mineral Veins by Later Metallic Sulphides," *Bulletin of the Geological Society of America*, 1900, vol. xi., pages 179 to 206.

$CaCO_3 + 2H_2O = PbCO_3 + CaSO_42H_2O$. In this manner, cerussite, formerly extensively mined in this district, was formed.

If the zinc sulphate reacts on calcium carbonate, smithsonite is produced, according to the following reaction:—$ZnSO_4 + CaCO_3 + 2H_2O = ZnCO_3 + CaSO_42H_2O$.

In this district, the bulk of the zinc sulphide seems to have been altered to the silicate [$(ZnOH)_2SiO_3$]. Silica in chert is abundant in the district, and this, in the presence of zinc sulphate and water, reacts as follows:—$SiO_2 + 2ZnSO_4 + 3H_2O = (ZnOH)_2SiO_3 + 2H_2SO_4$.

The iron present alters to ordinary limonite ($Fe_2O_33HO$) and hæmatite ($Fe_2O_3$), in the latter form giving the red colour to the gangue-clays, which is characteristic of the ore-bodies of this zone. Basic ferrous sulphate is a common bye-product.

### 4. Recapitulation.

The ore-bodies of the Missouri-Kansas district consist essentially of lead and zinc sulphides, with minor amounts of carbonates, silicates, etc. These ore-bodies chiefly occur in the Carboniferous Limestones and chert, which are capped by erosion-remnants of Coal-measure shales and sandstones, and are underlain by the Eureka-Kinderhook shale, which cuts them off from the Cambro-Silurian dolomites below. The beds have a gentle dip to the north and west, and the older beds crop out at higher altitudes than the younger. The ores were deposited from the underground-water solutions. These waters were in circulation, the motive power being gravitative stress, and the deposition occurred mainly as a result of the mingling of solutions, the sulphate solutions of the Cambro-Silurian passing up through the Eureka-Kinderhook, along fault-planes, and mingling with the reducing solutions of the Carboniferous Limestones. The ores were originally deposited as sulphides, and have since been reconcentrated by the downward flow of surface-waters with the production of an upper surface-zone of carbonates, silicates, etc., and a middle zone of enriched sulphides. Another result has been the production of an orderly vertical arrangement of the sulphides.

## C. *South-eastern Missouri District.*

In the South-eastern Missouri district the ores occur in the Cambro-Silurian limestone, which rests upon Cambrian sandstone, which in turn reposes upon pre-Cambrian rocks. While the fact has not been previously emphasized, shales occur frequently in the lower part of the Cambro-Silurian limestone, some distance above the Cambrian sandstone. The productive area is limited by an escarpment of Carboniferous Limestone, and at an earlier period this limestone, with Kinderhook shales at its base, doubtless covered the district. The ore-deposits occur in the Cambro-Silurian limestone associated with and overlying the shales belonging to the lower part of this limestone. The rocks have a dip away from the Archæan core to the Missouri and Mississippi rivers; that is, to the north, east and north-east. It, therefore, appears that the general facts in this district are remarkably similar to those in the Missouri-Kansas district.

As to the character of the ores, there are two distinct sub-districts in which the occurrences are markedly different. Following Mr. Winslow's classification,* the first of these is the St. François and Madison counties sub-district; and the second includes the Washington and Franklin counties sub-district, that is, the remainder of the South-eastern district. The latter sub-district will be considered with the Central district.

The first sub-district, that of St. François and Madison counties, contains the largest and most important lead-mines of Eastern Missouri. Mr. Winslow describes five camps in this sub-district, namely, (1) Mine La Motte, (2) Bonne Terre, (3) Flat River, (4) Doe Run and (5) Avon.† At all of these areas the ores are galena. The galena, for the most part, is disseminated through solid crystalline limestone, in many cases rather evenly, but in some cases, as in the Mine La Motte deposits, "grains of galena are frequently strung-out along the stratification, sometimes so close together as to form sheets, which vary in thickness from one-tenth to several inches."‡ Disseminated galena is also found as a matrix of conglomerate between boulders at the Doe Run mines.§ The Mine La Motte disseminated ores occur principally at two horizons. "The limestone of the upper horizon is known as the 'black rock,' of the lower as the 'white rock'; the ore is more persistent in the 'white rock.'"¶ Blende is very subordinate, and at the Bonne Terre camp "absolutely no zinc occurs, not even enough to be detected by analysis."||

* "Lead- and Zinc-deposits," by Mr. Arthur Winslow, *Missouri Geological Survey*, 1894, vol. vii., page 645.

† *Ibid.*, page 646. ‡ *Ibid.*, page 653. § *Ibid.*, page 673.

¶ *Ibid.*, page 653. || *Ibid.*, page 666.

In the Mine La Motte and Flat River areas, the ore is notably rich at the lower part of the magnesian limestone, where there are interstratified layers of slate. In some of the camps, early workings developed concentrated deposits of galena in crevices. For instance, at the Bonne Terre, "near the surface concentrated deposits of galena were found in crevices; and in the days of early mining these were the principal ores worked . . . . Several such crevices were developed and worked here, but they were all found to grow narrower, and to become unproductive with depth."* At the Flat River mines also "large amounts of massive galena were mined from crevices by shallow diggings."† But at present the ore "consists principally of galena disseminated through magnesian limestone,"‡ and these disseminated ores are at a greater depth than the galena in the crevices. The early workings also developed considerable cerussite, as for instance, at the Mine La Motte and Bonne Terre mines. The associated ore-bearing minerals are iron-pyrites and copper-pyrites, and cobalt sulphide and nickel sulphide. It is notable that the copper-pyrites carrying workable amounts of nickel and cobalt at Mine La Motte are found in the upper of the two horizons at which the ore occurs—the "black rock," rather than the "white rock." Also at the Bonne Terre mines, "the copper-pyrite and pyrrhotite, carrying about 4 per cent. of nickel and cobalt, characterized the upper workings down to a depth of 100 feet or so; although such ores are reported as occurring at lower levels."§ As in the south-western district of Missouri, pyrite is subordinate in quantity.

The chief gangue-minerals are calcite and dolomite, and it is notable that baryte is absent, although so abundant in the second sub-district of South-eastern Missouri and in the Central district.

The first four of these groups of mines are among the deepest lead- and zinc-mines of the Mississippi valley. For instance, the ores of the Mine La Motte area are mostly found between 70 and 150 feet from the surface.¶ The richest horizons of the Bonne Terre area are between 150 and 250 feet from the surface.‖ However, in those two areas, the crevice-deposits above described were at higher levels. In the Flat River area, most of the ore is below the 150 feet level; much of it is between 200 and 300 feet from the surface; and the lower level of the Central Mining Company, is 380 feet deep.* The Doe Run mines are principally between 50 and 90 feet from the surface, but galena has been developed to a depth of 230 feet. Finally, the ores in this district are associated with zones or belts of fracturing and faulting, just as in the Southwestern district.†

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* "Lead- and Zinc-deposits," by Mr. Arthur Winslow, *Missouri Geological Survey*, 1894, vol. vii., pages 650 to 669.

† *Ibid.*, page 668. ‡ *Ibid.*, page 668. § *Ibid.*, page 666.

¶ *Ibid.*, page 653. ‖ *Ibid.*, page 666.

It appears clear that these facts indicate two concentrations, the first by a deep circulation mainly between the shales near the bottom of the Cambro-Silurian limestone and the Eureka-Kinderhook shales, and between the lower shale and the underlying crystallines. At the time of this deep circulation, the disseminated ores in the limestones and shales were deposited. The reducing and precipitating agents were clearly derived from the organic matter of the shales and subordinately from the limestone. It is notable that the deposits in which the evidence points to a first concentration, with comparatively little effect by a secondary concentration, occur in the district in Missouri, in whch there has been the deepest mining.

When the overlying shales were removed by erosion, there began the second concentration by descending waters; and at this time the disseminated ores were taken into solution and concentrated in the crevices, as in the Mine La Motte and Bonne Terre areas.

The disseminated lead sulphide of the first concentration was oxidized to sulphate. The sulphate was largely carried downward by descending waters, and by reactions between that compound and the reducing solutions of the ascending currents, or the marcasite, or the organic matter of the formations, or by two or all combined, was reprecipitated as sulphide, thus resulting in a second concentration.

At the upper levels, mainly above the level of the ground-water, lead carbonate (cerussite) was formed by reactions between lead sulphate and calcium carbonate, as already explained. The presence of the rich deposits of copper-pyrites and pyrrhotite carrying workable quantities of nickel and cobalt at Mine La Motte and Bonne Terre at the upper horizons, and their absence at lower horizons, is further evidence of secondary concentration at upper horizons. Indeed, the production of these richer sulphides at higher horizons, and their absence at lower horizons, corresponds precisely to the facts upon which have been based the belief that two concentrations of such deposits have widely occurred; the first by ascending, and the second by descending waters.*

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* "Lead- and Zinc-deposits," by Mr. Arthur Winslow, *Missouri Geological Survey*, 1894, vol. vii., page 669.

† *Ibid.*, page 673.

The two exceptional facts of this sub-district, as compared with other districts, are the very great sparseness of zinc-ores and the absence of baryte.

### D. *Central Missouri District.*

With this district will be considered the sub-district of Washington and Franklin counties, belonging to the South-eastern district, since in all essential geological conditions the relations of this sub-district are closer with the Central than with the South-eastern district.

The Central district of Missouri and Washington and Franklin counties show the same geological succession as St. François and Madison counties. The occurrence and character of the ores are, however, very different. As shown by Mr. Winslow's† descriptions and figures, the ores occur almost exclusively in crevices, pitches, flats and caves. The occurrences of the ores are practically identical with those of Wisconsin, described by Prof. Chamberlin,‡ many years earlier, but here later considered. The ores occur lining the walls of the openings, or detached from them by solution. The mines are mostly shallow, nearly all less than 100 feet, being mainly above the level of the ground-water. In this respect also they are identical with the Wisconsin district, at the stage of development when Prof. Chamberlin described it. Moreover, the ores are of the same kind as they are in Wisconsin near the surface, that is, the ores are oxidized lead and zinc products and galena, and in this respect are identical with the Wisconsin ores. Thus, at the Jumbo shaft, dry bone and cerussite were found near the surface.§ At the Valle mines, a very large amount of zinc-ore has been mined, mostly as carbonate but to some small extent as silicate.* In some places, as for instance at Lee's diggings, pyrite is found below the galena.† Up to the present time, the amount of blende is subordinate, but it occurs to some extent associated with the galena. Workings as yet have not in general gone deep enough to show whether or not blende-deposits usually exist below the galena horizon, as in the Missouri-Kansas district. But important bodies of blende have already been developed at this horizon in the Meremac mine in Washington county and several mines in Morgan county. In most marked contrast with the mines of St. François and Madison counties, baryte is everywhere abundantly found. Mr. Arthur Winslow's descriptions mention baryte as a prominent gangue-mineral in almost every mine, and in a number of places it is so abundant as to become a valuable bye-product, as at Belfontain, Kingston and the Parole mines. Potosi and Mineral Point are important shipping-stations for this mineral.

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* "Some Principles controlling the Deposition of Ores," by Prof. C. R. Van Hise, *Transactions of the American Institute of Mining Engineers*, 1901, vol. xxx., pages 109 to 114.

† Mr. Arthur Winslow, *cit.*, vol. vii., pages 677 to 722.

‡ "The Ore-deposits of South-western Wisconsin," by Prof. T. C. Chamberlin, *Geology of Wisconsin*, 1882, vol. iv., pages 451 to 482.

§ Mr. Arthur Winslow, *cit.*, vol. vii., page 683.

The lithological succession of the Central district of Missouri and of Washington and Franklin counties, the position of the ore-bearing strata between impervious shales, the correspondence of the inclination of the beds and the drainage, and the fact that this inclination is greater than the slopes so as to cause lower horizons to crop out at the higher elevations, the manner of the occurrence of the ores, and the nature of the ores themselves, are all very like the Missouri-Kansas district already described; and still more like, indeed almost identical, with the upper district of Wisconsin, Illinois and Iowa, to be later considered. If the explanation of two concentrations, one by a deep circulation while the overlying shale was mainly above the ore-bearing strata, and a second concentration by descending waters after the impervious strata were removed, be correct for the Missouri-Kansas district, it is sure to apply to the portion of Missouri under discussion.

However, by comparing these districts with the St. François and Madison counties sub-district in Missouri, we note additional links in the chain of evidence for two concentrations. The relative sparseness of zinc-ores in the St. François and Madison counties sub-district has been emphasized.‡ Also the almost universal absence of baryte has been noted. But it has been explained of the central district and of Washington and Franklin counties that the zinc-product is very considerable; and that baryte is universally present and at many of the mines exceedingly abundant. It has been pointed out,* that the occurrences in St. François and Madison counties indicate that the deep disseminated ores are mainly the product of a first concentration by a deep circulation. The ores were mainly precipitated where they are, by the reducing action of the solutions produced by the organic material. Under these circumstances, there would be no reason for the formation of baryte. It is believed that the relative unimportance of the zinc is explained by the fact that the first concentration was not sufficient to produce large quantities of these ores. However, in the Central district, and in Washington and Franklin counties, a second concentration by descending waters became the controlling factor in the present location and distribution of the ores. Here, a second concentration produced zinc carbonate in sufficient abundance to be mined and also concentrated the lead, mainly as galena.

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* Mr. Arthur Winslow, *cit.*, vol. vii., page 687.

† *Ibid.*, page 690.

‡ *Trans. Inst. M.E.*, 1902, vol. xxiii., page 402.

If barium were present as a constituent of the associated rocks, so that barium salts would be carried by the underground solutions, the formation of the gangue-mineral baryte would be an incident of the second concentration. When the lead and zinc sulphide of the first concentration formed below the level of the ground-water, came above that level as a result of denudation they were oxidized to sulphates, as already explained. Also, it has been seen that these compounds react upon the alkaline-earth carbonates, producing carbonates of lead and zinc and sulphates of the alkaline earths.

Simultaneously the associated cerussite and smithsonite would be formed. Supposing the barium were in the form of carbonate, the reaction would be as follows:—$PbSO_4 + BaCO_3 = BaSO_4 + PbCO_3$; and $ZnSO_4 + BaCO_3 = BaSO_4 + ZnCO_3$.

If the barium were in some other form than carbonate, the reactions would also involve the carbonates of the other alkaline earths, calcium and magnesium, but the results would be the same so far as the barium is concerned. Ordinarily, the chief sulphate of the alkaline earths, formed as an incident to the development of cerussite and smithsonite, is gypsum. But where barium is present the sulphate of this metal would be precipitated because it is so much more insoluble than calcium sulphate. That barium was contained in the solutions in this district is evidenced by the abundant development of baryte as a gangue-mineral where a secondary concentration by descending waters has taken place. In this connection it is suggested that an investigation of the character of the limestone of the Eastern Missouri district will show that barium is a more important constituent than in Southwestern Missouri or in the Upper Mississippi valley, where baryte as a gangue-mineral is subordinate.

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* *Trans. Inst. M.E.*, 1902, vol. xxiii., page 404.

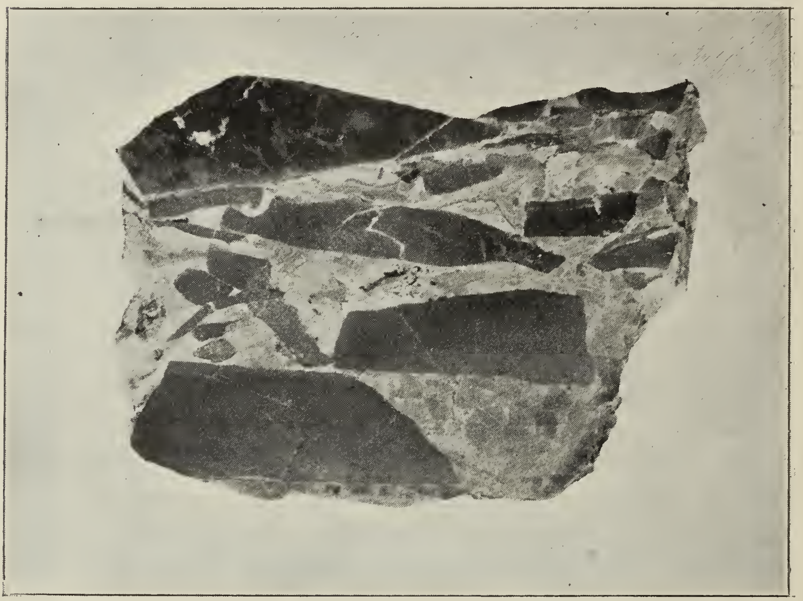

FIG. 13.—CHARACTERISTIC ORE-BRECCIA FROM THE MICHIGAN MINE, BUFFALO, NORTH ARKANSAS.

### E. *North Arkansas District.**

The ores of the North Arkansas district may be classed as (1) crevice-deposits; (2) breccia-deposits, representing zones of crushing in limestone or in limestone-conglomerate; and (3) disseminated ores in limestone or limestone-conglomerate. All of these deposits are in the Cambro-Silurian limestone. The crevice-deposits are similar to those of Central Missouri. The breccia-deposits, which are now the chief source of ore, have formed along zones of crushing. The character of these breccias is illustrated in Fig. 13, in which the dark fragments are pieces of the original country rock. The matrix is secondary dolomite, in which the blende is crystallized. The disseminated deposits are in the solid limestone, or the comparatively unaltered conglomerates. The ores comprise both lead and zinc, the latter being very important. Zinc occurs both as sphalerite and as smithsonite.

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* "The Zinc- and Lead-region of North Arkansas," by Dr. J. C. Branner, *Annual Report of the Arkansas Geological Survey for 1892*, 1900, vol. v., pages 1 to 393.

Dr. Branner[*] strongly insists that the ores are largely concentrated in local synclines, and that the anticlines are relatively barren, a relationship previously made out in Wisconsin by Prof. T. C. Chamberlin.

It is not possible to make any positive statements, at the present time, as to the manner of concentration of these deposits. Nevertheless, it seems highly probable that in this district, as in the others of the Ozark region, there have been two concentrations: (1) by a deep-seated artesian circulation, and (2) later concentration by descending water.

In the present state of knowledge no definite opinion can be expressed as to the relative influence of these two circulations; but it may be suggested that the rather large areas of disseminated ores in the compact limestone and unbroken conglomerate represent the work of a first concentration, and that the deposits containing oxidized ores associated with the sulphides in the crevices and breccias have undergone an important secondary concentration by descending waters.

## V.—The Upper Mississippi Valley Region.

### *Wisconsin-Iowa-Illinois District.*

In the region of the Upper Mississippi valley, there is only one district, that of Wisconsin-Iowa-Illinois.

This district was the first one in the Mississippi valley to be extensively studied, and nearly every notable advance in the genesis of the ores has been first worked out in this district. The early studies by Mr. J. D. Whitney,[†] followed by those of Prof.

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[*] Dr. J. C. Branner, *cit.*, page 32.

[†] *The Metallic Wealth of the United States*, by Mr. J. D. Whitney, Philadelphia, 1854, pages 403 to 417. "Report of the Geological Survey of Iowa, 1855-57;" and "Chemistry and Economic Geology," by Mr. J. D. Whitney, *Geology of Iowa*, 1858, vol. i., part 1, pages 286 to 295 and 422 to 471. "Report on the Lead-region of Wisconsin," by Mr. J. D. Whitney, *Geological Survey of Wisconsin*, 1862, vol. i., pages 73 to 424. "Geology of the Lead-region of Illinois," by Mr. J. D. Whitney, *Geological Survey of Illinois*, 1866, vol. i., pages 153 to 207.

T. C. Chamberlin,[*] in particular have done much to make clear the origin and nature of these ore-bodies.

As the result of the most excellent work of the Second Wisconsin survey under Prof. T. C. Chamberlin,[†] and the later work of the Iowa Survey,[‡] we give the descending succession in the lead- and zinc-districts of the Upper Mississippi valley as follows:—

Cincinnati shale, originally 200 feet thick (in Iowa called the Maquoketa shale).

Galena limestone, bearing organic matter, 450 feet thick.

Trenton limestone, bearing organic matter, 40 to 100 feet thick, with a mean of 70 feet, having at its top an oil-bearing shale[§] "2 or 3 to several feet in thickness at points," and containing throughout its mass various shaly layers, which, however, are "quite decidedly most prevalent near the base of the formation."[‖]

Generally at the base of the Trenton is "a greenish-blue clay, usually from 1 to 2 feet thick. The clay is very finely laminated, and consists of argillaceous and calcareous matter."[¶]

St. Peter's sandstone, 50 to 150 feet thick.

Lower Magnesian limestone, 100 to 250 feet thick.

Potsdam sandstone, 700 to 800 feet thick.

Pre-Cambrian.

It is to be noted that the Galena limestone is bounded by shales above and below, and that the same statement applies generally but not universally to the Trenton limestone. It is well known that shales are impervious to underground-water circulation. As to the impervious character of the thick Cincinnati shale above the Galena there is no doubt. One might, however, question the imperviousness of the thin beds of shale at the top and the bottom of the Trenton, but that the upper at least is relatively impervious is indicated by the fact that in the Shullsburg and other districts, as pointed out by Mr. W. P. Blake,* the ore-deposits frequently stop at the top of this layer. While the impervious shales of the Trenton are prominent at the top and near the bottom of the Trenton limestone, there are also more or less impervious layers within the limestone itself. The general similarity of the lithological sequence to that of the Ozark region is striking.

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[*] "The Ore-deposits of South-western Wisconsin," by Prof. T. C. Chamberlin, *Geology of Wisconsin*, 1882, vol. iv., pages 365 to 572.

[†] Prof. T. C. Chamberlin, *cit.*, page 412.

[‡] "Lead- and Zinc-deposits of Iowa," by Mr. A. G. Leonard, *Iowa Geological Survey*, 1897, vol. vi., pages 20 to 23.

[§] "Wisconsin Lead- and Zinc-deposits," by Mr. W. P. Blake, *Bulletin of the Geological Society of America*, 1894, vol. v., pages 28 to 29; also, "The Lead- and Zinc-deposits of the Mississippi Valley," by Mr. W. P. Blake, *Transactions of the American Institute of Mining Engineers*, 1894, vol. xxii., pages 629 to 632.

[‖] Prof. T. C. Chamberlin, *cit.*, page 409.

[¶] "Geology and Topography of the Lead-region," by Mr. Moses Strong, *Geology of Wisconsin*, 1878, vol. ii., page 683.

The strata dip to the south-west. Prof. T. C. Chamberlin says for Wisconsin, "the strata on the north side of the lead-region are 500 feet higher than those of the south side, and if traced farther the difference in altitude would be found greater. Beds on the eastern side are 350 feet higher than those on the west side."† Superimposed upon the general south-western monocline of the district are a number of subordinate anticlines and synclines, and the ores, according to Prof. Chamberlin, are confined mainly to the synclines.‡

The rocks are traversed by two complex systems of intersecting vertical joints and in some places by more. Locally, minor faulting also occurs. The folding and the fracturing of the brittle limestone were simultaneous processes. But, during the deformation, the plastic shales were mainly flexed, although in places they may have been dissevered by faulting. The time at which the deformation occurred is not definitely known, but in all probability it antedated the deep erosion and the concentration of ores in the district.§

Areally the ores occur to a much greater extent east of the Mississippi river than west of it; that is, mainly east of the principal line of drainage. As to horizons, by far the greater quantity of ores as yet abstracted were found in the Galena limestone.‖ However, considerable quantities of ores have been taken from the Trenton, and subordinate quantities from the St. Peter's sandstone and the Lower Magnesian limestone. The ores occur in the Galena from top to the bottom.

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* *Transactions of the American Institute of Mining Engineers*, 1894, vol. xxii. page 631.

† Prof. T. C. Chamberlin, *cit.*, page 422.

‡ Prof. T. C. Chamberlin, *cit.*, pages 432-438.

§ "Lead- and Zinc-deposits of the Mississippi Valley," by Mr. W. P. Jenney, *Transactions of the American Institute of Mining Engineers*, 1894, vol. xxii., pages 208 to 209. "Discussion of Mr. Jenney's paper," by Mr. Wm. P. Blake, *cit.*, pages 628 to 629, and Prof. T. C. Chamberlin, *cit.*, pages 427 and 485.

‖ Prof. T. C. Chamberlin, *cit.*, pages 407, 457 and 481.

In cases where erosion has not cut deep into the Trenton, the ore-deposits are apt to be found near the overlying Cincinnati shale. For instance, in Iowa, where the shales are close at hand as a continuous formation, Mr. A. G. Leonard states that the ore occurs mostly near the top of the Galena limestone, within the upper 50 or 60 feet.* Where the drainage-lines have cut through the Galena into the Trenton or lower formations, the ores of the Galena are likely, in large measure, to be near the bottom of the formation, and considerable bodies may rest upon the oil-rock which marks the beginning of the Trenton.

The broad facts as to the occurrence of the ores in the limestones are as follows:—

In openings in limestones, lead- and zinc-minerals are associated with marcasite, and some pyrite and chalcopyrite.† Calcite is an abundant gangue-mineral, as would be expected, but it and the other gangue-minerals will not here be taken into account. Since the pyrite and chalcopyrite are very subordinate, they will not again be alluded to. All the sulphide of iron will be referred to as marcasite.

The vertical order of occurrence in the district is commonly as follows:—Above the level of the ground-water in the belt of weathering the dominant valuable minerals are galena and smithsonite. Frequently encrusting the galena, or in crystals upon it, is some cerussite, and less anglesite; with the smithsonite there is some sphalerite. The smithsonite may locally occur to some extent, to a depth as great as 15 to 30 feet below the level of the ground-water; but deeper down the oxidized products almost wholly disappear. The smithsonite below the level of the ground-water is explained:—(1) By the material being often along a main channel of downward percolating waters; (2) by the fact that the level of the ground-water is probably now higher than it once was, as a result of depression and valley-filling at the close of the Glacial Epoch; (3) by the well-known general downward movement of oxidizing water somewhat below the level of the ground-water; and (4) by reactions between the oxidized lead salts and the sphalerite. Below the galena and smithsonite, that is, mainly below the level of the ground-water, is sphalerite, with a large amount of marcasite.

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* "Lead- and Zinc-deposits of Iowa," by Mr. A. G. Leonard, *Report of the Iowa Geological Survey*, 1897, vol. vi., pages 43 and 61.

† Prof. T. C. Chamberlin, *cit.*, pages 380 to 393.

Where the workings have extended to a considerable depth, the sphalerite is subordinate, the dominant sulphide being marcasite; but many of the workings have not pentrated to a sufficient depth to show whether or not this is general. For much of the district the workings have not gone far below the level of the ground-water, and consequently only the smithsonite and galena and the upper part of the sphalerite have been exploited. But during the past few years a considerable number of mines have penetrated 35 to 70 or more feet below the level of the ground-water. In the deeper of these workings, the sphalerite and marcasite are constantly associated, and the smithsonite and the galena are practically excluded. It may be further said that the few workings which have extended below the Trenton oil-rock have shown great proportional increases of marcasite.

While the above general statement is correct for the district as a whole, it must not be understood that a single sulphide occurs at a given level to the exclusion of the others. Indeed, in many cases all the sulphides are found at the same level. Prof. T. C. Chamberlin* states that, in the upper parts of the deposits of the Galena limestone, the order of arrangement of the materials from the walls to the druse is commonly:—(1) Marcasite and (2) galena in cubic crystals. But in many cases, the marcasite has been dissolved between the galena and limestone, thus loosening the galena-crystals. In some cases, also, a later deposit of marcasite coats the galena. Lower in the Galena limestone, the common order from the wall to the druse is:—(1) Marcasite, (2) ferriferous sphalerite, and (3) galena in cubic crystals. In some places there is superimposed upon this succession, the following members:—(4) Ferriferous sphalerite, subordinate in quantity; (5) marcasite; and (6) galena in octahedral crystals, very subordinate in quantity. As a result of working some distance below the level of ground-water, since Prof. T. C. Chamberlin's report was published, it has been ascertained that at these deeper levels the almost universal order from the wall is:—(1) Marcasite; and (2) sphalerite, galena being very subordinate.

* "The Ore-deposits of South-western Wisconsin," by Prof. T. C. Chamberlin, *Geology of Wisconsin*, 1882, vol. iv., pages 491 to 497.

It is believed, as fully explained in the general discussion at the end of this paper, that a large part of the material of these ores was once disseminated through the sedimentary rocks, and especially the limestones. The ore-bodies of the district were produced by the concentration of this material in and near the crevices.

Messrs. Whitney and Chamberlin believe that the deposits have been produced by a single concentration, by descending and lateral moving waters traversing the rocks in the immediate vicinity of the ores formed. Prof. T. C. Chamberlin holds that the movement was accomplished by the mingling of waters which came directly from the surface with waters which came somewhat less directly from the surface, moving downward and laterally. He says that: —

> At the time the ore-deposition took place, the openings in which the metals were deposited were being continually supplied with water from the two sources above indicated, namely:—(1) That which entered directly from the surface-opening of the fissure and was charged with organic matter, and (2) that which penetrated through the minute pores and fissures of the rock on either side of the crevice, and, becoming mineralized, found its way into the crevices. There thus came together, (1) water slightly charged with metallic substances, and (2) water slightly charged with organic matter. The result would be the reduction of the metallic compounds to sulphides, by the deoxidizing action of the organic matter.
>
> It would only remain for the metallic sulphides to gather on the walls of the crevice in their appropriate crystalline forms to produce the galenite, blende, pyrite, marcasite and chalcopyrite that formed the original deposit.

However, Prof. T. C. Chamberlin* recognizes that the organic matter in the bed-rocks themselves also served as a reducing agent. Thus is explained the impregnation of the carbonaceous beds with crystals of galena, blende and pyrite.

The above process described by Prof. T. C. Chamberlin is similar in many respects to that already given for the reconcentration or secondary enrichment of the ores of the Ozark region. In the Wisconsin-Iowa-Illinois district, the many analogies of the structural relations of the ores to the containing rocks, the character of the ore-bodies themselves, and the vertical distribution of the ores of different kinds, to those of the Ozark region, give strong reasons for believing that the processes which operated in the latter region were also influential in the former district: that is, there was an early concentration by an artesian circulation, which produced lean ore-bodies of a greater vertical magnitude than the deposits now existing, and a reconcentration by a shallow circulation. The general character of this earlier circulation, and some of the reasons for believing that it was here influential, may be briefly stated as follows :—

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* Prof. T. C. Chamberlin, *cit.*, page 545.

While in the Wisconsin lead-district the Niagara limestone and Cincinnati shale are only found on occasional mounds, as pointed out by Prof. T. C. Chamberlin,* there is no question that these formations once extended over the entire district. As already noted, the Cincinnati shale is an impervious stratum. Until it was cut through by the drainage, it is probable that effective concentration of the ores did not begin. When it was once cut by erosion, the main concentration history of the ore-deposits is believed to have begun. The Mississippi river and areas adjacent were the places where the drainage was the lowest. However, these were not the places first cut through by erosion, for the difference between the level of the Mississippi drainage and the tributaries adjacent is not so great as the dip of the strata to the south-west. In all probability, therefore, the Cincinnati was first cut through, and the Galena encroached upon by erosion north and east of the lead- and zinc-district. This is probable from the fact that, at the present time in the lead-district, the Mississippi river is for the most part on the Trenton limestone, and never reaches deeper than the St. Peter's sandstone ; while the majority of the smaller streams in the north-eastern part of the lead-district have cut into the St. Peter's, and the headwaters of some of them, notably the Pecatonica, Platte and Grant rivers, have cut through the St. Peter's into the Magnesian ; and still farther to the north-east, north of the divide, occupied by the Lancaster branch of the Chicago and North Western railway, the strong Wisconsin has cut down to the Cambrian.†

It is to be remembered that the pervious strata overlain by impervious strata along the Mississippi river bear water under pressure, as is shown by numerous artesian wells.‡ The feeding area is the higher ground to the north-east. It is highly probable that the broken and consequently porous Galena limestone was a formation which was capable of carrying water to considerable distances, and in considerable quantities, although probably not comparable in these respects to the St. Peter's or Potsdam sandstones. The lead- and zinc-district of Wisconsin is wholly south of the divide between the Wisconsin river and the tributaries of the Mississippi. When the Wisconsin drainage north of the divide had cut through the Cincinnati shale, this furnished a feeding area to the Galena limestone. When, later, the Mississippi tributaries south of the divide had cut through the Cincinnati shale into the Galena, the waters entering to the north-east and following along the limestone were able to escape to the south-west.

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* Prof. T. C. Chamberlin, *cit.*, pages 410 to 412.

† See *Atlas of Wisconsin*, plates i. and viii.

‡ "Artesian Wells of Iowa," by Mr. W. H. Norton, *Iowa Geological Survey*, 1896, vol. vi., pages 113 to 428.

As erosion continued, the area in which the Cincinnati was cut through and the Galena was penetrated gradually extended to the south-west, until the Mississippi itself had cut through the Cincinnati. During this time, the water entered the Galena limestone at the higher elevations, that is, to the north and east, followed along this formation, and escaped at some lower point towards the Mississippi river. While the water to the greatest extent followed the upper portion of the Galena, it is believed that this broken formation, and to an unknown extent all the lower sedimentary formations, were searched to their deepest parts according to the laws of the flow of underground water.

It is well known that during the early part of the journey of underground waters they contain oxygen and, therefore, produce an oxidizing effect upon the compounds with which they come into contact. Also, when the waters first enter the ground they contain no salts in solution and are, therefore, dissolving waters. Waters which have had a long underground journey are apt to be reducing. This is especially likely to be true if they are shut off from the surface by impervious strata. For instance, the artesian waters in the vicinity of Lake Michigan and along the Mississippi river, the feeding area for which is Central Wisconsin, are "marked by slightly sulphuretted waters."*

Concerning the circulation, it is here sufficient to say that the meteoric water entering the earth at innumerable points occupies the entire available cross-section in its journey. In the early part of its course, where it is widely dispersed, its vertical component is downward. This component is superimposed upon a lateral component giving resultant curved lines of flow. As the water continues its journey, it is more and more converged into trunk-channels. In the latter part of its journey in these trunk-channels, the vertical component is upward. The lateral component of the journey is frequently a hundred or more times as great as the vertical component. Finally, the upward component of the water in the trunk-channels carries it to the surface, where it escapes.

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* "The Ore-deposits of South-western Wisconsin," by Prof. T. C. Chamberlin, *Geology of Wisconsin*, 1882, vol. iv., page 547.

In the Wisconsin limestone, the trunk-channels through which the water mainly escaped were joints. These joints, in this district, are called "crevices." As already noted, in many parts of the district the crevices occur in two intersecting sets* and at such places of intersection it is well understood by mining-engineers that the ore-deposits are likely to be unusually rich. In the early part of the journey, where the water was recently derived from the surface and was widely dispersed, it has been seen that the waters are oxidizing and dissolving. The conditions were, therefore, favourable to the oxidation of minute dispersed sulphides of lead and zinc to sulphates. Once oxidized, these metals would be taken into solution.

While the lead and zinc have been supposed to be carried as sulphates this is not a necessary supposition, for they may have been transported in part or in whole in other forms. The dissolved lead and zinc would be largely carried to the trunk-channels or their vicinity. Here, where the water was ascending, it is believed that the lead and zinc were largely precipitated as sulphides.

The precipitation of the ores in and adjacent to crevices is believed to have been due to the mingling of solutions adjacent to these trunk-channels. Portions of the solutions furnished the dissolved compounds. Such solutions would be likely to be those which utilized the large opening and which had not come into intimate contact with strata bearing abundant organic material. Other solutions which, in the late parts of their courses, came from limestone or shales containing organic matter were reducing and probably contained sulphydric acid, since, as already noted, the deep artesian waters of the present circulation of the region contain this compound. Other reducing compounds may have been carried in the waters. The mingling of these two classes of solutions in the trunk-channels would throw down the lead and zinc as sulphide, according to the following equation:—$PbSO_4 + H_2S = PbS + H_2SO_4$.

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* *Atlas of the Geology of Wisconsin*, plates xxxviii., xxxix. and xl.

It is probable that there was a tendency at the time of this first concentration in the crevices for the sulphides to be thrown down in a more or less definite order across the openings, as indicated by the phenomenon of crustification, although this phenomenon is probably largely explained by a later concentration.

However, the sulphates of lead and zinc of the solutions dispersed through the smaller openings of the rocks were doubtless in part reduced by the direct action of the organic material contained in the shales and limestones. In this case, the precipitated lead and zinc sulphides would be disseminated through the shale and limestone. They would be likely to be most abundant in shales and limestones containing organic matter, adjacent to a trunk-channel which furnished an abundant supply of metals; for a vigorous circulation is necessary to furnish a large supply of metals, and from the trunk-channels waters would continuously make their way into the adjacent carbonaceous rocks. In the lead- and zinc-district of Wisconsin, ores are now frequently found in so-called clay-openings. These clay-openings, to a considerable extent, represent shaly layers interstratified with the limestone, once containing carbonaceous material. Thus, the inference of the precipitation of the disseminated ores by the carbonaceous material is confirmed.

In the Wisconsin district, iron salts were far more abundant than lead and zinc salts, as is shewn by the very abundant associated iron sulphide. The process of transportation of the iron and precipitation as sulphide is precisely analogous to that of the zinc and lead.

The process above outlined continued for many centuries; perhaps for a geological period or more. By it there were finally locally concentrated along the crevices and disseminated through the limestones and shales adjacent to the crevices considerable quantities of lead and zinc sulphides associated with marcasite. As erosion slowly progressed, the zone of rising and escaping waters slowly migrated from the north-eastern part of the lead- and zinc-district to the south-western part. The circulation within the Galena limestone at a given time is roughly represented by Fig. 14, a north-east to south-west section. The surface of the country is shown by A, B, C, in which A, B, is the cross-section of a north-west and south-east belt, where waters enter, and C is in a parallel belt to the south-west, by which the waters escape.

The numerous curved lines below the Cincinnati shale are intended to represent the general lines of movement of the waters. The widely dispersed downward-moving lateral-moving waters, in the early stages of their journey, were oxidizing and dissolving waters. The upper-moving waters in the trunk-channels (AE) were precipitating waters, and the material was especially likely to be precipitated where the waters came into contact with abundant organic material.

The circulation was much more complex than is shown by Fig. 14. The circulation was not wholly delimited below by the Trenton shale. The water in its underground journey encountered not one crevice, but many crevices; moreover, these crevices were in intersecting sets. The movement of the water would be largely controlled by these fractures, and thus the deflections resulting from them would be almost indefinitely complex. However, it is believed that Fig. 14 represents the average movement of the water in the Galena limestone. The transference of the ore-material at this time was, indeed, exceedingly complex, but by the combination of all the factors considered the material was precipitated where the water was ascending in and adjacent to the trunk-channels, to a much greater extent than elsewhere. In an early stage of the first concentration by ascending waters, the process took place only in the north-eastern part of the district, for only in that part was the Cincinnati shale cut through and the porous Galena limestone exposed, so that the water was able to escape. From the north-eastern part of the district, the process extended to the south-west, as fast as the shale was here and there cut through by the streams.

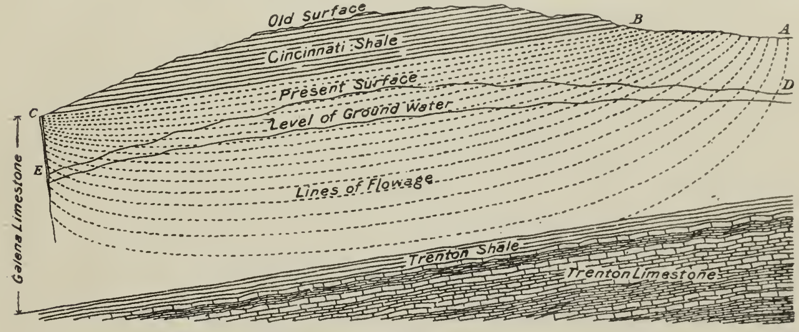

FIG. 14.—THEORETICAL NORTH-EAST TO SOUTH-WEST SECTION OF THE LEAD- AND ZINC-DISTRICT OF WISCONSIN.

By the time that erosion had cut through the Cincinnati shale into the Galena limestone, in the south-western part of the district, and ascending waters were concentrating ores, the north-eastern part of the district may have been a feeding area where waters were descending and where a second concentration was taking place. Therefore, the second concentration by descending waters was probably going on in the north-eastern part of the district at the same time as the first concentration by ascending waters was occurring to the south-west. At the present time, erosion has cut sufficiently deep so that the second concentration by descending waters has extended quite to the Mississippi river; and, indeed, to the west of it. At the present time, the condition of affairs as to the exposures of the formation is represented by Fig. 14 below the line DE, which may be taken as the present surface of erosion.

While it is possible that the vertical order of the minerals is to some small extent due to a first concentration, it is believed that the controlling factor in the regular vertical distribution of the galena, smithsonite, sphalerite and marcasite was the second concentration by the action of descending waters in connection with denudation. The order of the events and the nature of the reactions by which the second concentration took place are substantially like those which form the enriched sulphide ores and the oxidized ores in the Missouri-Kansas district, treated in an earlier part of this paper, and therefore the details of the process need not be repeated.

## VI.—Outlying Districts.

Apart from the four ore-bearing districts of the Ozark region and the Wisconsin-Iowa-Illinois district there are two districts in the Mississippi valley, which yield more or less lead and zinc. These are located in uplifts distinct from the Ozark, though possibly of the same age and genesis.

### A. *South Arkansas District.*

Throughout the Ouachita mountains, which lie to the south of the Ozark uplift and are separated from it by the Arkansas valley, lead and zinc occur. They are associated with silver, gold, antimony, and other metals not found elsewhere in the Mississippi valley. They occur in well defined fissure-veins, associated usually with a quartz-gangue. The ore-bodies show the same evidences of secondary enrichment as those which may be observed in the Ozark districts. The region is a difficult one in which to do geological work, and so far has not been studied in detail. It would be premature to express any opinion as to the first concentration of these ores.

### B. *Illinois-Kentucky District.*

The mines of this district were visited some years ago by Mr. S. F. Emmons,* and have recently been described by Mr. W. E. Burk.† The Illinois-Kentucky district is located mainly in Hardin and Polk counties, Illinois; and in Crittenden, Caldwell, and Livingston counties, Kentucky. Rosiclare, Illinois; and Marion, Crayneville, Fredonia and Crider, Kentucky, are the leading shipping-stations. The ores include both lead and zinc, which occur in intimate association with fluorspar, in small vertical veins or fissures which have very regular courses a little east of north. They are cut by numerous secondary cracks or cross-veins at a somewhat uniform angle. The main fissures can be traced for several miles. Important faults occur in the district. The country-rock is Lower Carboniferous limestone. The hills are capped by fragments of shaly strata belonging to the Coal-measures. At depths not yet reached in mining, the black shale of the Devonian and the underlying Cambro-Silurian dolomites should occur. The rocks of the district have, except locally, only slight dips. In general geology and in the form and shape of the ore-bodies, the district shows close similarity with the others already described. In the association of the ores with fluorspar, the district is at marked variance with the others. On this point, Mr. W. E. Burk may be quoted as follows: —

> Within the vein-walls there is but little country-rock, the filling being firm and fully crystallized. Most of the veins contain a clear transparent fluorspar, giving a snow-white appearance where granulated and shattered. In some veins, perhaps only those containing associated lead- and zinc-ores, the fluorite occurs (especially in open vughs) in well-developed cubical crystals possessing all the various tints through purple, from a pale amethyst to an intense, almost black purple. These crystals represent the last product of crystallization and there is some evidence that this colour is due to traces of certain metals found associated with the zinc and lead; possibly manganese. This presence of coloured fluorite has become a guide to prospectors, for while zinc and lead may not be actually

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* "Fluorspar-deposits of Southern Illinois," by Mr. S. F. Emmons, *Transactions of the American Institute of Mining Engineers*, 1893, vol. xxi., pages 31 to 53.

† "The Fluorspar-mines of Western Kentucky and Southern Illinois," by Mr. W. E. Burk, *The Mineral Industry*, 1901, vol. ix., pages 293 to 295.

present, it will usually lead to zinc at some further depth. In fact, there seems to be a sequence in this mineral deposit, and generally the fissures have not been worked deep enough to reach zinc- and lead-ore. This sequence, beginning with transparent or white fluorite, leads to a trace of lead ; then comes coloured fluorite with more lead and a trace of zinc. Following this, the fluorite gives place to calcite with more lead and zinc, and zinc predominates with some lead and a mixed fluorite and calcite-gangue. The Columbia mine near Marion, Kentucky, is by far the best known and developed mine operating. This seems to be at the centre of the local upheaval, and has a 6 to 8 feet fissure-vein. The sequence, if taken up at the surface with a showing of violet-coloured fluorite and considerable of zinc carbonate, changes at a little depth to lead and zinc sulphides, the fluorite giving place to calcite. With increased depth, the calcite or calcspar in turn diminishes, with fluorite disappearing almost entirely, and at a depth of 125 feet, the vein is uniformly zinc and lead sulphides from wall to wall, assaying from 30 to 50 per cent. metals. This sequence is in accordance with conditions at other mines in the district.

The Eagle fluorspar-mine near Salem, Kentucky, is now opened in a lower grade zinc-ore with fluorite present to the extent of 50 to 60 per cent., while some other fluorspar-mines in the district are at the point where too much lead and zinc is present for high-grade fluorite and too little lead and zinc as yet for mining operations for these metals. It is probable that all the main fluorite-veins (true faults) will lead at some considerable depth into lead and zinc.*

This association of the minerals, and their vertical sequence, are very suggestive indeed of a first concentration by a deep circulation, modified by a later reconcentration through surface-waters. It has been customary to refer these deposits to fumarole-action, because of the presence of fluorspar. No igneous rocks crop out in the vicinity, and except for the fluorspar, there are no apparent reasons for referring the deposits to different agencies from those at work in other parts of the Mississippi valley. If further studies should show that the deposits are wholly due to the usual genesis, an important addition will be made to the knowledge of the principles controlling the deposition of the ores, in that fluorspar as a necessary evidence of fumarole-action will be excluded. If, on the other hand, fumaroles were an agent in the production of the Illinois-Kentucky ores, these may still be in the main the result of the action of underground waters.

## VII.—General Discussion and Conclusions.

### A. *Immediate Source of the Metals.*

### 1. Lead and Zinc widespread in Limestones.

Large-quantity analyses by Mr. Robertson of the rocks of the Missouri districts show the presence of minute but important amounts of zinc and lead in the pre-Cambrian, Cambro-Silurian and the Carboniferous.[*] Analyses by Mr. Weems[†] show that the Ordovician rocks of the Iowa area also carry minute quantities of these metals. The facts of the field bear out the conclusions drawn from the analyses. It is a matter of common observation throughout the Mississippi valley that the limestones contain minute quantities of various metallic sulphides.[‡] Along the western slope of the Appalachians are occasional occurrences of both lead and zinc.

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* "The Fluorspar-mines of Western Kentucky and Southern Illinois," by Mr. W. E. Burk, *The Mineral Industry to the End of 1900*, 1901, vol. ix., pages 294 to 295.

2. Material of Limestones adequate to account for Ore-deposits.

It is therefore clear that the limestones of the Mississippi valley are a source from which the ore-deposits could have been derived. The next question to be considered is whether the residual amounts of these widely dispersed, minute quantities of lead and zinc are sufficient to render it probable that the limestones originally contained an adequate amount of metals to account for the ore-deposits. Upon this point the calculations of Mr. Buell seem to be decisive.

According to Prof. T. C. Chamberlin,[§] Mr. Buell has calculated that if the source of the metal in the Potosi area, one of the richest in the Wisconsin district, be restricted to a layer of limestone 100 feet thick, and limited on the outside of the area of paying crevices by half the average distance between the crevices, to account for all the lead which has been taken out, it would only be necessary to suppose that the rock yielded "one fourteenhundredth of one per cent., or a little more than one seven-millionth part of the rocks.[‖]

In the limestones of many districts, both analyses and observation indicate the presence of more lead and zinc than this; and therefore the amount contained is adequate to account for the ore-deposits.

3. Ores derived from the Cambro-Silurian Limestone.

But, so far as the analyses are concerned, the ore might be derived from any of the limestone-formations of the Mississippi valley or from the pre-Cambrian rocks; and the next point which needs to be considered is from what source the underground waters actually did derive the metals. This question has already been answered by the full discussion of the circulation of the underground waters in the various districts and the manner of the segregation of the ores. The relations are particularly clear in the Ozark region. The circulation in the formation which contains the most widely-dispersed ores, the Cambro-Silurian, is mainly in that formation and confined between the pre-Cambrian and the Eureka-Kinderhook. It is therefore natural to suppose that the greater quantity of the ore was derived from the Cambro-Silurian; although it is entirely possible that considerable quantities may have been derived from the underlying pre-Cambrian. It has been further seen that, while within the Missouri-Kansas district the main ore-deposits are found in the Carboniferous, the supply for these ore-bodies came from the rocks below, and, therefore, that the source of this material is the same as the deposits in the Cambro-Silurian limestone itself. In other districts of the Mississippi valley, the artesian circulations in the Cambro-Silurian were to a considerable extent limited below by shaly formations at the bottom of the limestone, thus largely confining the circulation to this formation, the limits of ready movement being the shales above and below it. In these cases, it is very probable that the main source of the material is the Cambro-Silurian limestone.

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[*] "Lead- and Zinc-deposits," by Mr. Arthur Winslow, *Missouri Geological Survey*, 1894, vol. vii., pages 479 to 482.

[†] "Geology of Dubuque County," by Messrs. Samuel Calvin and H. F. Bain, *Annual Report of the Iowa Geological Survey for 1899*, 1900, vol. x., page 567.

[‡] Messrs. S. Calvin and H. F. Bain, *cit.*, pages 569 and 570.

[§] "Ore-deposits of South-western Wisconsin," by Prof. T. C. Chamberlin, *Geology of Wisconsin*, 1882, vol. iv., page 538.

[‖] Prof. T. C. Chamberlin, *cit.*, page 538.

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Another argument in favour of the derivation of the ores from the Cambro-Silurian limestone is furnished by the porosity of the Cambro-Silurian as compared with the pre-Cambrian. In order to have filled cavities and produced ore-deposits, the water-circulation must have been active and long-continued.

Water issuing at the surface from mineral springs generally contains not more than 1 part of silica in 100,000.* Therefore, if as much silica be deposited in a cavity as ordinarily issues at the surface, it is necessary to assume when a cavity becomes filled with silica that at least 260,000 times as much water has passed through the cavity as would fill it. The amount of lead and zinc in solution in spring-waters has been very rarely determined. Mr. A. C. Peale† gives the amount of zinc, measured as sulphate, in seventeen cases, and as a bicarbonate in one case. In the remaining analyses quoted by Mr. A. C. Peale, zinc is not reported at all, or is given merely as a trace. Therefore, it may be assumed that spring-waters in the lead- and zinc-districts of the Mississippi valley carried somewhat more than the average amounts of these metals. Mr. A. C. Peale's determinations may be accepted as the best approximation towards average conditions available, and the average amount determined as zinc sulphate by him was 0·22 grains per gallon. If all of this be supposed to be precipitated as sulphide, it would require approximately 1,000,000 times as much water to pass through a given cavity as would fill it before the cavity would be closed by precipitation.

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* "Lists and Analyses of the Mineral-springs of the United States," by Mr. A. C. Peale, *Bulletin of the United States Geological Survey*, 1886, No. 32, page 235.

† "Mineral-springs of the United States," by Mr. A. C. Peale, *Bulletin of the United States Geological Survey*, 1886, No. 32, pages 49, 59, 62, 64, 65 and 67.

Since the metals were present in adequate quantity and the conditions for solution favourable in those rocks through which the bulk of the waters passed, the larger amount of ore was probably derived from them.

Therefore, it is believed that the Cambro-Silurian is the main source of the ore-deposits; although it is recognized that if in the pre-Cambrian rocks lead and zinc were abundant a smaller amount of water passing through these rocks would be the source of a large amount of ore. However, there is little evidence that the pre-Cambrian rocks are richer in lead and zinc than the Cambro-Silurian limestone. Indeed, if one takes the presence of widely dispersed, small quantities of lead and zinc in the two rocks as evidence as to the original amount present, there was probably less in the pre-Cambrian than in the Cambro-Silurian. It therefore appears to us that there is every reason to suppose that the main source of material for the ore-bodies was the Cambro-Silurian limestone.

### B. *Original Deposition of Lead and Zinc in Dolomitic Cambro-Silurian Limestone.*

It has been seen that analyses show the presence of lead and zinc in both the Cambro-Silurian and Carboniferous limestones. The association of lead and zinc with limestones throughout the world is very close and has often been the subject of comment. Limestone, however, has been used to include both magnesian and non-magnesian rocks. In literature, the distinction between the two kinds of rocks has not always been preserved. It is probable that the association is more common with dolomitic than with non-dolomitic rocks.* If it were possible in every case to determine just what kind of rock is included under the term "limestone," the association of the metals with the magnesian rather than non-magnesian rocks probably would appear much clearer.

Very generally throughout the Mississippi valley, the Cambro-Silurian is so magnesian as to be called the Magnesian series.

In the Mississippi valley, it is certain that there is a very close association of the lead- and zinc-metals with dolomite and magnesian limestone. This is evidenced by the number of profitable districts which occur in this limestone, but in a still more marked way by the sparsely disseminated lead and zinc throughout vast areas of this limestone. Illustrating the general fact of the occurrence of lead and zinc in the magnesian rocks, and ignoring for the moment the productive districts, it may be said that throughout the Niagara of Wisconsin and Iowa, small amounts of galena and blende are found, and in the entire Ozark region small amounts of lead and zinc are found in practically every county where the Cambro-Silurian is exposed. Now turning our attention to the productive districts, in practically every area where ores are mined in the Mississippi valley, dolomite occurs abundantly in intimate mixture with the ores, or in the immediate vicinity of the ore-bodies.

This statement is true even of the Missouri-Kansas district, where there are very large and important ore-bodies in a Carboniferous limestone, which, as a whole, is non-magnesian; but, even here, these ores are associated with dolomitization of the country-rock. This association of the ores of this district with dolomite has been frequently noted. But it has been fully explained,† that the source of the ores and the dolomite alike is the Cambro-Silurian limestone. Therefore this district affords no exception to the rule that the original home of the ores of the Missisippi valley is magnesian limestone.

The reasons which may be assigned for the association of lead and zinc with magnesian limestones are to some extent theoretical. It has been common to consider the association wholly due to secondary causes. Dolomite is a porous rock, and hence is extensively traversed by large volumes of underground waters. Its homogeneity causes it to fracture in extensive planes, and so trunk-channels for circulation are opened through it. It is a rock which may be believed to absorb ores selectively from solutions coming from extraneous sources. It is particularly subject to metasomatic replacement. But none of the explanations which regard as due to secondary introduction the very sparsely disseminated minute quantity of lead and zinc in the magnesian limestone of the Mississippi valley seem to us adequate to explain the facts. It seems to us that the very widespread presence of lead and zinc compounds in magnesian limestone strongly suggests that the original introduction of the lead, zinc and magnesium in the rock was simultaneous. After the three materials had been deposited in the rock the law of mass-action accounts for their common transportation and segregation. The constant association of the three metals leads to the hypothesis that the primary association is due to the fact that the conditions under which large areas of dolomitic limestone formed are favourable to the deposition from the sea of minute quantities of metallic sulphides. This hypothesis has been developed elsewhere,* but will be here outlined.

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* "Geology of Dubuque County," by Messrs. Samuel Calvin and H. F. Bain, *Annual Report of the Iowa Geological Survey for 1899*, 1900, vol. x., page 573.

† *Trans. Inst. M.E.*, 1902, vol. xxiii., page 395.

Many years ago Prof. J. D. Dana showed that complete dolomitization of recent coral-formations has taken place upon the island of Metia. This dolomitization he explains as due to the reaction between the waters of the sea in shallow lagoons and the fine calcareous ooze. He states that "in such lagoons, mainly shut-off from the sea, and therefore in a 'salt-pan' condition, the concentrated brines contained the magnesium chloride and sulphate in a state that favoured the formation of dolomite."† He suggests that dolomite "owes its origin at times if not always" to such conditions.‡

In the Iowa area, the Galena-Trenton formation includes a partly dolomitized series of limestones. Dolomitization extends irregularly from the top downwards and is regional, not being associated with definite cracks and water-channels as in the Carboniferous Limestone of the Joplin area. The dolomitization occurred very early, seemingly immediately after the limestone was deposited, if not during the deposition. There is evidence that the rocks were formed under shallow-water conditions, but in the portion dolomitized there is no evidence of nearness to shore.

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* "The Geology of Dubuque County," by Messrs. Samuel Calvin and H. F. Bain, *Annual Report of the Iowa Geological Survey for 1899*, 1900, vol. x., pages 573 to 575.

† *Manual of Geology*, by Prof. Jas. D. Dana, fourth edition, 1895, page 133.

‡ *Ibid.*, page 133.

Thus in certain districts the facts correspond to the conditions under which Prof. J. D. Dana has observed dolomitization; and it seems to us probable that the general dolomitization of the Cambro-Silurian limestone of the Mississippi valley took place in large part at least while the limestone was still below the sea by the reactions between the magnesium-solutions in the sea and the deposited calcium carbonate.

Deep-sea dredging has shown that the reduction of various salts to sulphides by organic material is widespread along the sea-bottom. If Prof. J. D. Dana's conclusion as to conditions most favourable to dolomitization be correct, the process is likely to have taken place to more than an average amount where "salt-pan" conditions were approximated. If it be a general fact that lead and zinc occur in large amounts in areas where dolomitization is farthest advanced, as a result of conditions of unusual concentration of the sea-salts, it is a natural suggestion that under these same "salt-pan" conditions the lead and zinc salts were also concentrated. Therefore, where dolomitization is far advanced, there, probably, more than an average amount of sulphides was precipitated by the organic matter.

### C. *Localization of the Ore-deposits.*

In connection with the above, the question naturally arises as to the localization of the ores within definite districts of the Cambro-Silurian limestone, and in small areas within those districts. It has been seen that between the productive districts are great barren regions, and between the productive areas within each district are barren areas smaller than those between the districts, but still large as compared with the highly productive areas.

It seems to us that the localization into districts and areas is largely explained by the peculiar combination of factors which characterize the districts where the ores occur:—(1) They are at places where there has been an early deep artesian circulation between confining shales, and later a surface-circulation; (2) they are at places where the rocks have been fractured by extensive crevices or faulting, or both ; (3) such places are trunk-channels for circulation; and (4) the ores occur at places where reducing agents could be supplied for the precipitation of the ores.

If the ores were somewhat evenly distributed throughout each district, it might be supposed that the limestones of these particular districts was originally richer in lead and zinc than the main areas of Cambro-Silurian limestone ; but when it is recalled that within each district there are areas of extraordinary richness separated by many areas of greater size which are almost or quite barren, it is hard to believe that there could have been within a district such sudden variations in the original amount of lead and zinc carried in the limestone. Therefore the explanation of the extreme localization within the district lies mainly in the factors above mentioned, and not in original variation in the amount of material in the limestone.

The same explanation may be applied to the localization into districts, and thus the large barren areas may be explained ; but Prof. T. C. Chamberlin doubts whether the unusual facilities for segregation in certain areas is a sufficient cause for the localization of the ores.* He suggests that the localization is due to exceptional original concentration adjacent to lands where the sea-waters may be supposed to have contained more than an average amount of lead and zinc, and in areas of the Cambro-Silurian limestone where eddies or Sargasso seas gathered very large amounts of sea-weed to serve as a reducing agent.† But the fact that the lead and zinc were not concentrated in the Carboniferous Limestone at the time of its deposition at a period during which organic matter must have been more abundant than in Cambro-Silurian time, raises the question whether or not, if there were original concentration in certain districts, it is not adequately explained by unusually favourable chemical conditions for precipitation which were connected with the dolomitization. It has been noted that while there is regional dolomitization in the Cambro-Silurian of the Mississippi valley, the amount of magnesium is very variable. In this connection, the junior author has ascertained that in the Iowa area the productive points are in the areas in which the regional dolomitization is in the most advanced stage; and he offers the suggestion already advanced,* that the same concentration of sea-salts which probably produced dolomitization also resulted in precipitation of more than the usual amount of lead and zinc. However, it remains a very open question as to whether or not in the Cambro-Silurian limestone there was originally an unusual amount of segregation of lead and zinc in the productive districts, as compared with the non-productive barren areas.

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* The Ore-deposits of South-western Wisconsin," by Prof. T. C. Chamberlin, *Geology of Wisconsin*, 1882, vol. iv., page 529.

† Prof. T. C. Chamberlin, cit., pages 529 to 538.

### D. *Segregation of Ore-bodies from the Cambro-Silurian Limestone.*

The next general point in the chain of events is the segregation of the ores from the Cambro-Silurian limestone. This subject has been fully treated in the discussion of the various districts. In that discussion it has been assumed that the source of the ore was the Cambro-Silurian limestone, and with that hypothesis the segregation has been traced out. It is here, therefore, necessary only to summarize the main conclusions which have been reached in that discussion.

#### 1. Lithological Succession.

Considering the Mississippi valley lead- and zinc-regions as a whole, disregarding the names of formations, and considering only the lithological succession in each district, we have in descending order:—(1) Thick shale formation; (2) limestone, bearing ore-bodies; (3) shale; (4) limestone, bearing ore-bodies; (5) shale, often interstratified with limestone; (6) sandstone; and (7) pre-Cambrian. In some of these districts, a portion of these formations have been removed by erosion. Excluding the little-known outlying districts, in all of the important districts, except the Missouri-Kansas district, all of the ores occur in the Cambro-Silurian limestone.

#### 2. Vertical Distribution of Ores.

Wherever the full vertical distribution of ores is known, it is essentially the same in each of the districts. Oxidized zinc- and lead-ores with galena occur above and near the level of the ground-water. Below the level of the ground-water are zinc sulphides with subordinate quantities of lead sulphide, and with increase of depth iron sulphide increases and locally becomes dominant. In these statements, the ores which occur in the crystalline rocks of Missouri are not considered, and to them the statements as to the vertical distribution are not applicable.

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* *Trans. Inst. M.E.*, 1902, vol. xxiii., page 428.

The segregation of the ores is regarded as due to two concentrations. The first circulation was mainly within the limestones between the bounding shales. The water entering the limestone at the surface-outcrops passed down and along the limestone-formations until crevices or faults were found through which it might ascend and escape. At such places, the waters from various sources mingled, some bearing the metallic materials and some bearing reducing agents. The materials were thrown down as sulphides; and so far as can be made out, these sulphides had no regular vertical distribution. As already explained, the sources of the materials for the solutions were the metals in the limestones through which they passed. Thus, the first concentration was accomplished. As denudation continued, the shales overlying the limestones were removed. As soon as water was able to enter at places where there had been a first concentration, a second concentration began. As a consequence of this second concentration, the rich oxidized products were formed above and near the level of the underground-water, and the rich sulphides within a comparatively short distance below the level of the ground-water, as fully explained in the discussion of the individual districts.

## VIII.—Conclusion.

If the general theory above given be correct, there were three stages of concentration of lead and zinc in the Mississippi valley:—(1) A concentration to a minute fraction of 1 per cent. in the Cambro-Silurian limestone at the time of its deposition; (2) a concentration by an artesian circulation early in the erosion-history of the region; and (3) a reconcentration by a shallow circulation in the later stages of the erosion-history.

If this outline be correct, the lead- and zinc-ores in all the districts of the Mississippi valley furnish excellent illustrations of that class of ores produced as a result of a concentration by ascending waters and a later concentration by descending waters. Moreover, all these districts illustrate with remarkable clearness the very important influences of impervious strata in the development of ore-deposits. Finally, these deposits illustrate beautifully that comparatively shallow circulations may at the point of precipitation deposit ores by ascending waters, and that later such ores may have been reconcentrated by descending waters.

The similarity as to the lithological succession, the occurrence of the ores, and the genetic relations between the ore-deposits and the stratigraphy in widely separated districts in the Mississippi valley seems nothing short of marvellous. Identity seems the only word which fits the case for several of the districts. Whether the above explanation of this similarity be absolutely correct or not, there can be no doubt that the same general explanation is applicable to all the districts. One cannot be explained in independence of the others or in a radically different manner.

If the theory here proposed be compared with those advanced by earlier workers in this region it will be seen to differ from each, and yet to combine features of all. The ascensionists, as typified by Messrs. Percival* and W. P. Jenney,† are followed to the extent that it is believed that ascending waters have been important in the production of the ore-bodies. This is particularly clear in the case of the ores of the Missouri-Kansas district, the one studied in most detail. The ideas advanced differ from those of Messrs. Percival and W. P. Jenney in that these ascending waters are not believed to have been derived from an indefinite and unknown depth, and are not believed to have been heated. They are merely a portion of the general circulation which at the point of deposition has, as a result of the combined action of geological structure and gravitative stress, an upward movement.

We agree with the descensionists, Messrs. J. D. Whitney,‡ T. C. Chamberlin§ and Arthur Winslow,¶ on the fundamental point of deriving the ores from the surrounding rocks. We agree to some extent with Mr. Arthur Winslow's conception of the residual concentration of the ores, so far as applied to the ores here defined as within the zone of oxidization. We further agree with Mr. J. D. Whitney and Prof. T. C. Chamberlin in the general action of descending waters, but differ in regarding this as following an earlier concentration by a deep circulation.

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* Mr. — Percival, *First Annual Report of the Geological Survey of Wisconsin*, 1854, pages 30 to 33; and *Annual Report of the Geological Survey of Wisconsin*, 1856, page 63.

† "Lead- and Zinc-deposits of the Mississippi Valley," by Mr. W. P. Jenney, *Transactions of the American Institute of Mining Engineers*, 1894, vol. xxii. pages 219 to 223.

‡ "Report of the Lead-region of Wisconsin," by Mr. J. D. Whitney, *Geological Survey of Wisconsin*, 1862, vol. i., pages 398 *et seq.*

§ "The Ore-deposits of South-western Wisconsin," by Prof. T. C. Chamberlin, *Geology of Wisconsin*, 1882, vol. iv., pages 544 to 549.

¶ "Lead- and Zinc-deposits," by Mr. Arthur Winslow, *Missouri Geological Survey*, 1894, vol. vii., pages 467 *et seq.*

As to the extent of the application of the theory, we hold that the evidence already collected warrants the belief that the main outlines are certainly applicable to the Missouri-Kansas district, and are very probably applicable to the other districts of the Mississippi valley.

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The President (Mr. J. S. Dixon) moved a vote of thanks to Messrs. C. R. Van Hise and H. Foster Bain for their paper, which formed a most valuable addition to the *Transactions*.

Mr. C. C. Leach seconded the resolution, which was cordially approved.